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# CORROSION RESISTANT, NOMETALLIC WATER WELL SYSTEMS

P. E. Hudson

F. W. Nobles

Radian Corporation

TECHNICAL REPORT NO. AFWL-TR-72-146

May 1973



AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico



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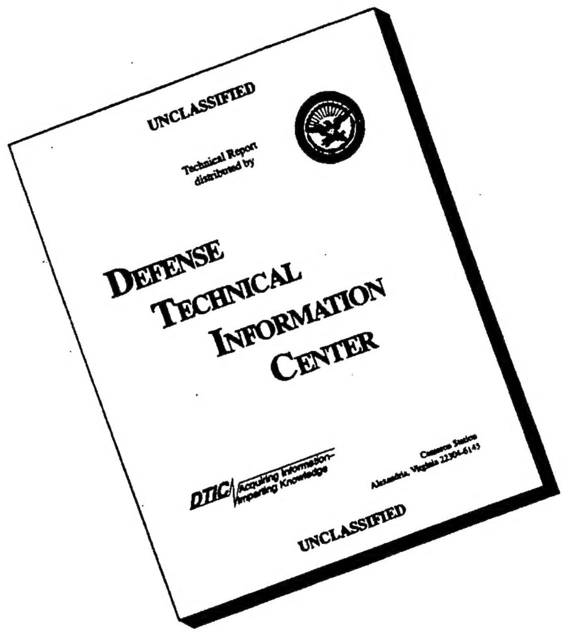


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# FOREWORD

This report was prepared by the Radian Corporation, Austin, Texas, under Contract F29601-70-C-0030. The research was performed under Program Element 63723F, Project 683M, Task 5.

Inclusive dates of research were February 1970 through July 1972. The report was submitted 16 March 1973 by the Air Force Weapons Laboratory Project Officer, Lt Colonel Doctor S. Morrisey (DEZ-B).

I would like to acknowledge the assistance of Captain Bertran Ruggles and Lt Colonel D. S. Morrisey (AFWL). I would also like to acknowledge the helpful discussions with Dr. J. R. Meyers of the Air Force Institute of Technology, and Lieutenant Majchrowski for his assistance in the preparation of this report.

This technical report has been reviewed and is approved.

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## ABSTRACT

(Distribution Limitation Statement A)

The use of fiberglass reinforced plastic pipe for water well applications was investigated. To carry out this investigation, a test program and test procedures were developed due to the unavailability of uniform test methods for plastic pipe for this application. The apparatus necessary for the test program, including long and short term tension tests as well as biaxial, point and uniform load compression tests and combinations of these tests, was constructed and the tests performed on commercially available plastic pipe from several manufacturers. The results of these tests allow comparisons of the physical properties of the nine manufacturers' pipe tested. These data are compiled in such a manner that they can be utilized to design an optimum well system for any particular installation.

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## SECTION I

## INTRODUCTION

The objective of this project was to test and evaluate fiberglass reinforced plastic pipe for use in water well systems. The resulting data are then organized in a manner that will allow specifications to be prepared for a particular installation.

This report is divided into two volumes. In this volume, volume I, the data are presented in graphical form, and reasonable judgments are made of the effectiveness of fiberglass reinforced materials applied to water well systems. In addition, the equipment description and methods needed to test the material are included. A relative cost analysis of a shallow well is made considering the various brands of FRP pipe and common and stainless steel. Examples of using these data to prepare specifications are also presented in this volume. Volume II contains the point-by-point data collected by Radian Corporation.

The United States Air Force is constantly faced with the problem of maintaining its water supply at the many Air Force installations around the world. This problem exists in part because of the premature failure of water well casings, screens, and drop piping due to rapid corrosion of these components. The premature failure of one or more of these components is generally caused by the corrosivity of the water and the soil. The most common cause of water well corrosion is water which contains dissolved acid gases such as $CO_2$ or oxidizers such as $O_2$. This component failure due to corrosion not only results in costly repairs, degraded water, or permanent loss of a well, but can severely compromise the operational status of the installation.

Since the worldwide operations of the Air Force require vast amounts of potable water, the elimination of the costly and

recurring interruptions of the production of this water is highly desirable. One such possibility lies in the development of non-metallic water well components that can compete structurally and economically with the present metallic systems. The nonmetallic material evaluated in detail in this program is fiberglass reinforced plastic (FRP). Because of its many desirable features, fiberglass reinforced plastic pipe is becoming more widely used as both column and casing pipe in water wells. Some of its qualities, including lightweight, easily assembled connections, and corrosion resistance, have become particularly attractive. In situations where skilled labor is not available, transportation costs are high or where the consequences of material corrosion would compromise a large installation, the advantages of fiber-reinforced plastic pipe are worth consideration.

Radian Corporation has designed a series of tests to compare the material properties of various fiber-reinforced plastic pipe products. This program was necessary because a uniform series of tests is not presently being used throughout the plastics industry. Slight deviations in test equipment or procedure can significantly change the results of a particular test. In developing the test program for this project, the goal was to utilize tests that would, as nearly as possible, be representative of the type stresses the materials would encounter in the field.

During the installation and operation of a water well, the pipe is subjected to several mechanical forces. The first stresses to consider occur during the installation of the well casing itself. One force will be given by the weight of the well casing. The maximum tensile force will be encountered when a casing is pulled from the well. The test program must therefore include tensile tests to define the upper limit the pipe can be subjected to. A discussion concerning the drilling and finishing of a well is contained in Appendix I.

When the outer casing is set, the screen is gravel packed and the rest of the hole is grouted. During these operations as well as after these are completed, external pressures can arise, for instance by caving or movement of the formation. These pressures may be uniformly distributed over a greater surface area or be more localized in case the caving formation contains rocks. The parallel plate test and the tup test appear to simulate both extremes satisfactorily. It is possible that the integrity of the entire structure could be compromised by a puncture since the stresses involved can be propagated through the entire circumference. The ability of the casing to localize a failure is apparent from the puncture test followed by a tension test. The screen itself is expected to be exposed to a more uniformly distributed compressive pressure, therefore the determination of its hydrostatic compressive strength is proposed.

The column pipe is subjected to a long-time tensile load applied by the weight of the submerged pump or turbine pumps and shaft and the weight of the water within the column pipe. Both the creep behavior over a long period of time and the tensile strength are therefore measured. It is possible that a long-term load or the exposure to water itself could seriously decrease the tensile strength of the pipe. The creep test followed by a tension test shows any such loss in tensile strength. In addition the long-term creep load and the exposure to water may cause a break in the glass matrix that would allow low-intensity point load to fracture the pipe. This effect is shown by the creep test followed by a puncture test. A potential weak spot could significantly affect the life of a water well system. A tup test followed by a creep test will show the long-term effects of this weak spot.

The exposure of the well parts to chemicals is of major importance in water well applications. When screening becomes

encrusted and decreases the well's capacity, treatments with acids are sometimes used. Also, chlorine treatments are used for disinfection and removal of slime which can seriously clog well systems. The excellent resistance of plastic pipe to a variety of chemicals is well documented in the literature. Additional supporting data are therefore not necessary.

## SECTION II

## DISCUSSION OF THE PROBLEM

Before a comprehensive testing program can be developed, it is necessary to understand the criteria that determine the usefulness of the product. The following sections contain a discussion of the types of problems that must be considered when selecting a material to be used in water well pipes and components.

### A. Mechanical Properties

During the entire process of well construction, the material used for casing and column pipe plays an important role. Although many different types of drilling rigs are available to drill wells into almost any soil configuration, some of the methods can be very demanding of the material strength which corresponds to the type of casing used. The reverse-rotary method has been used to install RFP water wells. In such instances the maximum tensile load on the casing is due to the weight of the casing. As is shown in the following sections of this report these loads are not excessive. After installation various compressive forces are placed on the casing due to the packing and shifting of the formation. The casing must resist this radial pressure without affecting the column pipe and without allowing undesired water to enter the well. The binding on the outside pipe wall due to the compression could also prevent the pipe from being pulled.

The well screen must be strong enough to withstand collapse of the surrounding formation in all wells. In cases where the screen is driven into the formation, such as driven well points, the screen must be able to resist the compressive and tensile stresses placed on it.

The column pipe must be able to support its own weight, pump weight and the weight and pressure of a long column of water. Also, it must resist fatigue fracture due to continuous vibration of the pump.

From these few examples, an appreciation of the importance of the material properties can be obtained.

B. Corrosion Resistance

To be suitable for use in water wells, materials must not only possess the proper mechanical properties, but they should also provide protection against the environment to which they are exposed. Although corrosion of water well systems is widely known as a singular significant problem, the causes of water well corrosion problems can be quite varied.

In metallic systems there are many possibilities for corrosion. Creating a galvanic cell through the contact of two dissimilar metals can be a frequent factor when inexperienced personnel are involved. One of the most common causes is the water itself. Water containing dissolved acid gases such as $CO_2$ or $H_2S$ or dissolved oxidizers such as $O_2$, can be extremely troublesome. In addition, water with a high dissolved solids concentration is better able to support corrosion because of its high conductivity.

When carbonates from the groundwater become encrusted in the screening sometimes acid treatments are used to remove the deposition. The screening must be able to withstand such treatments.

Present water well protection methods have a variety of shortcomings. Cathodic protection has proven successful in

protecting solid metallic underwater structures but is not as attractive when applied to water wells utilizing metallic casing and column pipe. Because of the nature of cathodic protection, only the exterior surface, in this case the outside of the casing pipe, is protected. Although this exterior surface is the only exposed surface in a solid member, both sides of the column pipe and the interior of the casing remain unprotected when used in water wells.

Coatings work well when a good bond is made to the parent material and no pores are present in the coating. Since it is virtually impossible to prevent scratching the coating during installation and since the attainment of a pore free coating is beyond the present state of technology, the benefit of a coating in water well usage is dubious. Corrosion will be concentrated at the pores and scratches resulting in faster penetration of the metal than might otherwise occur.

This brief discussion of the nature of the problems that may be encountered during and after water well construction places a large emphasis on both the mechanical and chemical properties of material to be used. It was with these problems in mind that fiberglass reinforced plastic pipe began to evolve as a possible solution. FRP combines the excellent chemical properties of plastics with the desirable mechanical properties of the reinforcement. This composite results in an unusual combination of possibilities both in construction procedure and material constituents that may provide the best answer to present corrosion problems.

## SECTION III

## TECHNICAL APPROACH

The research program that has been conducted at Radian Corporation consisted of nine major tests. The last four of these tests to be discussed are "combination tests." These tests add a more realistic appraisal of the condition the pipe actually placed in the hole. This potential loss due to a combination of failure effects is extremely important because failure due to a single cause is an ideal case. These tests are described below and are discussed in some detail elsewhere in this report. Where possible, the tests were run in accordance with the referenced ASTM method.

### A. Longitudinal Tensile Properties of Reinforced Thermosetting Plastic Pipe and Tube ASTM D2105-67

This test provides a variety of data that is of interest in water well construction. Tensile stresses are encountered in the casing and column pipe both during and after construction. The highest tensile stresses are created in the column pipe. The uppermost pipe in a string of column pipe is held at the surface while the remaining joints hang below. The dead weight of the pipe itself can be considerable in a deep well, but the added possibility of supporting a column of water from the bottom of the well to the surface, as is the case when submersible pumps are used, can create extremely high stresses.

The casing material can have the same dead weight tensile stress as the column pipe when it is being lowered into a hole that is standing open. If the hole is not straight, tensile stresses are created at the outside of the bend. In addition, earth movements can cause unavoidable bends in the hole over

either short or long periods of time which in turn produce tensile stresses. If the well is at some time abandoned, it is economically feasible to attempt to pull up the casing pipe. The dead weight plus the skin friction developed between the outer surface of the pipe and the soil will create extremely high stresses in the casing material.

The tests run by Radian are on 30-inch samples utilizing a 10-inch gauge length for measuring the strain. Gripping heads have been designed to achieve the necessary connection to the pipe specimen with a minimum of disturbance to the material itself. The head is self-energizing and of a simpler design than the one shown in the ASTM specification. The yoke that is used to provide the 10-inch gauge length is of the quick release type allowing the ultimate strength to be approached before the dial readings are discontinued for the actual failure.

The specimens are conditioned for 48 hours at the testing temperature before the actual test, which is run in general accordance with the ASTM guidelines. Tensile properties including the modulus of elasticity, yield stress, elongation beyond yield, tensile strength, elongation to break, and energy absorption can be calculated from the data obtained in this test.

B. External Loading Properties of Plastic Pipe by Parallel Plate Loading ASTM D2412-68

This test method covers the determination of load-deflection characteristics, calculation of the stiffness factor, and measurement of the load and deflection at rupture of fiberglass reinforced pipe under parallel loading. A test of this kind allows the engineer to ascertain the probability of well failure

caused by an event such as a bore-hole cave-in. The degree to which the pipe material can deflect without losing its integrity can become a major factor when natural earth movements occur. Compressive forces of this type will mainly concern the casing pipe and not the column pipe as, ideally, there will be a concentric gap between the two. A large radial deflection of the casing would be required before a compressive load could be exerted on the column pipe. The amount of deflection that is possible before failure of the casing material could dictate the most efficient column pipe to be used. The stiffer the casing material is under a compressive load, the larger the column pipe could be within it.

In this test the specimens will be three diameters in length so that comparable data can be obtained throughout the range of pipe sizes. This differs somewhat from the ASTM pipe diameter. The logic of the change made by Radian can be understood by the following illustration. In the extreme case, consider a 1-inch pipe and a 36-inch pipe. Taking a 6-inch section of both pieces results in two entirely different configurations. The 1-inch pipe specimen looks like a length of pipe while the 36-inch specimen appears to be more nearly a ring. A hoop of this latter type will be much more flexible in the lab test than in actual field tests of a joint of pipe under a similar loading. However, the 1-inch field data would be more similar to the test data because it was, relatively speaking, a long piece. It is felt that by using specimens of the same relative dimensions, a more comparable set of data will be obtained.

The rest of the test closely follows the guidelines made by ASTM.

C. External Loading Properties of Plastic Pipe by Point (Tup) Loading (Reference ASTM D2412-68 and ASTM D2444-67)

The point load test used by Radian is two test methods combined to achieve a meaningful design parameter for water well construction. There are many possibilities for a point load to be exerted on the well casing material. Perhaps the most significant of these is the stringing of a well through a boulder field. The sides of the well hole are seldom smooth surfaces but, rather, pieces of rock are often imbedded in the surrounding soil layers. When these rock particles come in contact with the well casing, a point loading situation can develop. Natural earth movements can impose high stresses over a small area of pipe surface. This type of localized load is an entirely different situation from a uniform load.

Since the distance that earth material will move during a down hole cave-in is relatively small, impact testing was not considered as important as a constant, slowly applied force of the type that would occur naturally. The point load apparatus suggested by ASTM for the impact test was, however, a reasonable choice for the method of application. A vee-block will be used to hold the pipe in position during the puncture test instead of any type of sand box support. The vee-block design is more consistent and easier to reproduce in other labs.

D. Hydrostatic Compressive Strength of Glass Reinforced Plastic Cylinders ASTM D2586-68

Of the material used in a water well, the screen material is most susceptible to collapse. Not only is it the section that is the deepest into the ground, but by its very nature

screen is less capable of withstanding the loads applied to it. The type of loading most likely to occur at the screen is a constant biaxial (radial) compression. Resistance to this condition is not easily measured by either a parallel plate or a point load test. For this reason a hydrostatic compression test has been devised to evaluate the various screen materials.

As the purpose of screening is to let water go through the casing pipe, a means must be devised to make the specimen watertight, in order to apply the load and, at the same time, not to influence the test results. A lightweight plastic sheet wrapped around the outside of the specimen and sealed at both ends is an acceptable method of achieving a watertight specimen. The plastic will in no way affect the validity of the test.

Obviously the ends of the pipe must be capped as well. A tapered "stopper" is used, in this case, with an internal structure to keep the cap from exerting any pressure on the pipe wall. In addition, the pipe interior is vented to the atmosphere through the end cap so that internal pressures cannot affect the test. These tests should give a good index of the loss of strength in the pipe when the glass fibers are cut for use as screen.

E. Testing Long-Time Creep and Stress Relaxation of Glass Reinforced Plastics under Tension at Controlled Temperatures

This test was originated by Radian Corporation to answer questions concerning the down hole condition of fiberglass reinforced pipe after long periods of time at a high working load. Wells have been drilled to extended depths where FRP is now in use. Many of these wells use a submersible pump to bring the water to the surface. This pump is attached to the

bottom of the column pipe and is used to "push" the water upward. When the pump is not in use, the column pipe remains full of water. This column of water can create a high stress in the pipe in addition to that already caused by the weight of the pump itself. Sufficient evidence was not available to determine the "stretch tendency" of FRP. If the pipe did stretch, it would be desirable to know how much and whether there is a loss in strength.

Radian Corporation has designed a test procedure to determine the creep characteristics of FRP. An axial tension load is applied to the pipe material and held for up to 1000 hours. At the same time, water at a temperature of 125°F is constantly circulated through the specimens. A 40-inch gauge length is used on a 52-inch specimen so that accurate readings can be maintained. High alloy springs are used to apply the load.

### F. Longitudinal Tensile Properties of Glass Reinforced Plastics Previously Exposed to Long-Time Creep

This test combines tests A and E above in order to determine what loss in tensile strength is due to water and long term loads on the pipe. The weight of the pump and water on the column pipe could possibly decrease the pipe's strength to the point where it could not support the required loads. In addition this test can help show if water itself can affect the FRP pipe.

The specimens are first creeped as described in Subsection E. On completion of the creep studies, a tensile strength test, as described in Subsection A, is run on 24-inch samples.

G. External Loading Properties by Point (Tup) Loading of Plastic Pipe Previously Exposed to Long-Time Creep

This test combines tests C and E above in order to determine if an extended axial load may weaken the glass matrix that would allow low intensity point loads to fracture the pipe.

The specimens are first creeped as described in Subsection E. On completion of the creep studies, a tup loading test is run on the specimen, as described in Subsection C.

H. Long-Time Creep and Stress Relaxation of Glass Reinforced Plastics Previously Exposed to a Point Load of 50% of the Puncture Strength

This designed combination test incorporates tests C and E described above. This test will show if a potential weak spot would significantly affect the life of the water well system. If the column pipe were damaged during installation, the long term life of the well could seriously be affected.

The specimen is first tupped to 50% of its strength as described in Subsection C. A sheet of rubber is then glued to the inside of the tup hole. In this way the pipe is made watertight but the seal does not interfere with the creep test. The creep test is then carried out as described in Subsection E.

I. Longitudinal Tensile Properties of Glass Reinforced Plastics Previously Externally Point (Tup) Loaded

This combination test combines tests A and C as described above. The ability of the pipe to localize a failure becomes apparent after this test. It is possible that the integrity

of the entire structure would be compromised by a puncture since the stresses involved can be propagated through the entire circumference. If the rock imposes a point load on the casing, the loss in tensile strength could be so great that it would be impossible to pull the casing. In addition it is conceivable that the weakened casing could pull apart by its own weight.

A specimen with a length/diameter ratio of three is first tupped, as described in Subsection C, and is then axially loaded to failure as described in Subsection A.

## SECTION IV

## DESCRIPTION OF TEST EQUIPMENT

The various equipment used by Radian to test fiberglass reinforced plastic pipe is discussed in the following sections. The object in designing the specific testing devices and procedures is to obtain data that will be useful in evaluating field conditions from laboratory studies. Each test is designed to simulate the mechanical forces which will act on the pipe during and after well construction.

### A. Tension Test

The tension test provides the data necessary to compute the load-strain characteristics of the FRP material. In addition, a value for the ultimate strength of both plain pipe and pipe connections can be determined.

One of the important parameters in a tensile test is the manner in which the specimen is gripped. The test results can be distorted until they are meaningless if proper considerations are not made when selecting the method for gripping the pipe. There are several alternatives including a V-type grip device that is standard for pulling rods but is not very applicable in the case of pipe or tubing. A special arrangement is necessary under these conditions to prevent collapse of the wall. Wall collapse is especially critical in the case of FRP as compared to steel because it is necessary to protect the resin layer in the pipe interior. A mandrel device is suggested by ASTM D2105 although a different configuration is used by some of the manufacturers in their own testing programs.

Radian combined the best components of all available systems to design a new but not totally different mechanism for gripping

the pipe specimens. The gripping device is an internally expanding, self energizing system with an adjustable collar on the outside of the specimen to restrain radial stresses (see Figure 1).

In all cases the loading rate is constant but not greater than 1200 lbs. per minute. The 4-inch specimens are tested on a hydraulic type machine and the larger specimens are tested on a gear driven universal loading machine.

Strain is measured by the movement of a lightweight extensometer that is attached to the pipe and utilizes a 10-inch gauge length. The jeweled Federal dial gauges, that are used for the actual measurement, are removed as the ultimate load is approached to protect them from possible breakage.

Tested in this manner the tension tests produced good reproducible data.

### B. Parallel Plate Loading Test

The parallel plate loading test uses the same basic methods as ASTM D2412-68. An "I beam," with attachments for mounting two Federal D815 dial gauges, is placed in a universal load machine so that the beam's lower surface is parallel to the base surface of the loading machine (see Figures 2 and 3). The lower flange surface is used to provide one of the parallel plates while the base table of the loading machine provides the other. The beam is designed so that there will be no deflection of the beam under the anticipated loads. Test specimens have a constant length/diameter ratio (L/D = 3) and are conditioned at the testing temperature for 48 hours. The specimens are measured to determine the point of minimum wall thickness. This

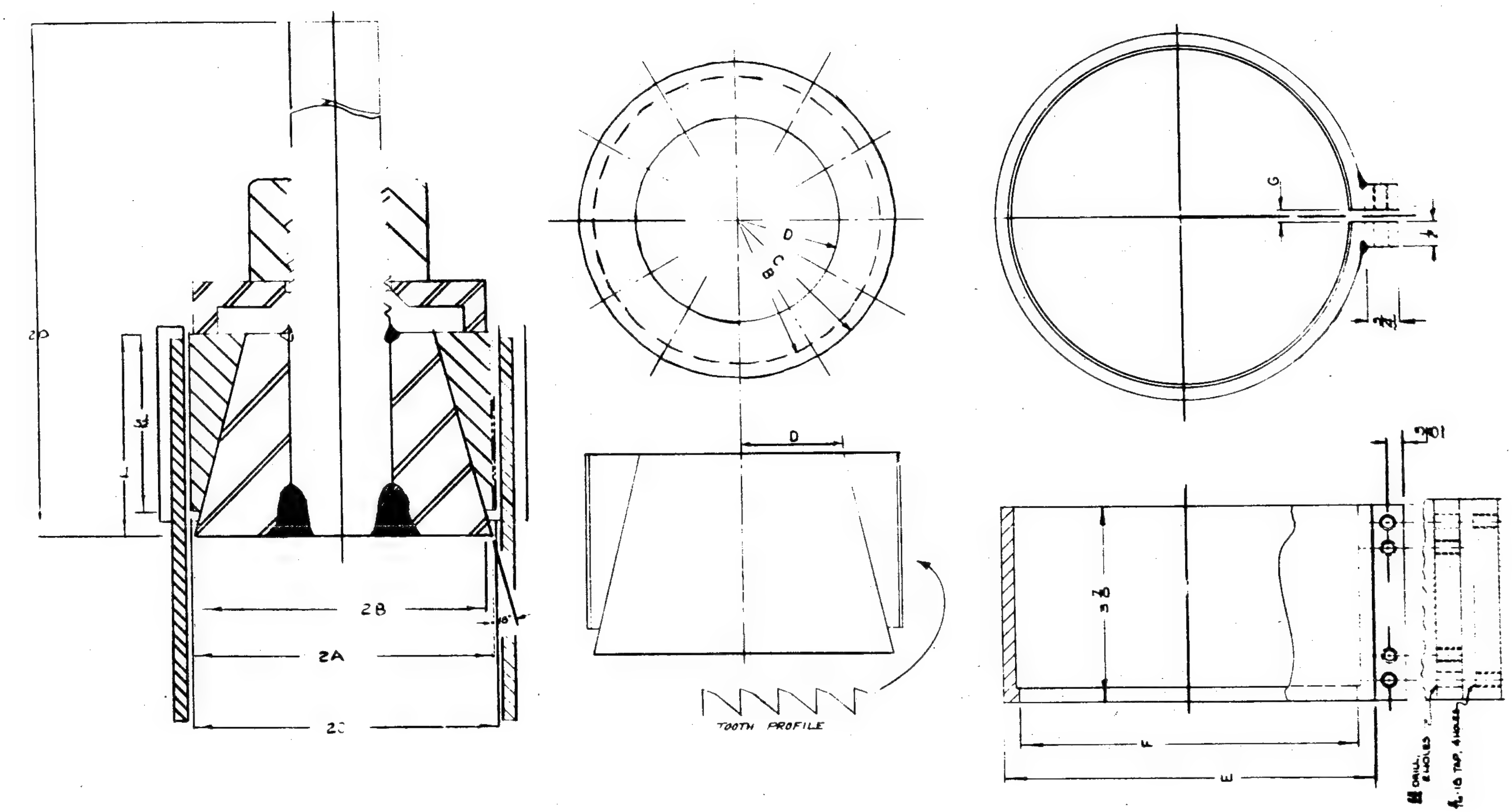



Figure 1. Grips for Tension Test

## EXPLANATION OF DIMENSIONS FOR FIGURE 1

A - The large radius of the cone. It is smaller than the minimum inside pipe radius.

B - The maximum inside radius of the gripping teeth.

C - The outside radius of the gripping teeth.

D - The small radius of the cone. A and D form an angle of 15°.

E-F - The thickness of the collar lip. It must be thick enough to resist the radial pressures, but thin enough to permit adjustment.

G - The slit width of the collar. It is chosen so that the smallest pipe can be securely held.

| Dimensions (in.) | Pipe Size (inches) 4 | 6 | 8 | 10 |
|---|---|---|---|---|
| A | | 2.975 | | |
| B | 1.75 | 2.735 | 3.95 | 5.0 |
| C | 2.0 | 2.985 | 4.20 | 5.25 |
| D | 0.88 | 1.860 | 3.05 | 4.0 |
| E | 2.5 | 3.615 | 4.83 | 5.825 |
| F | 2.0 | 3.115 | 4.45 | 5.45 |
| G | 0.75 | 1.0 | 1.0 | 1.0 |

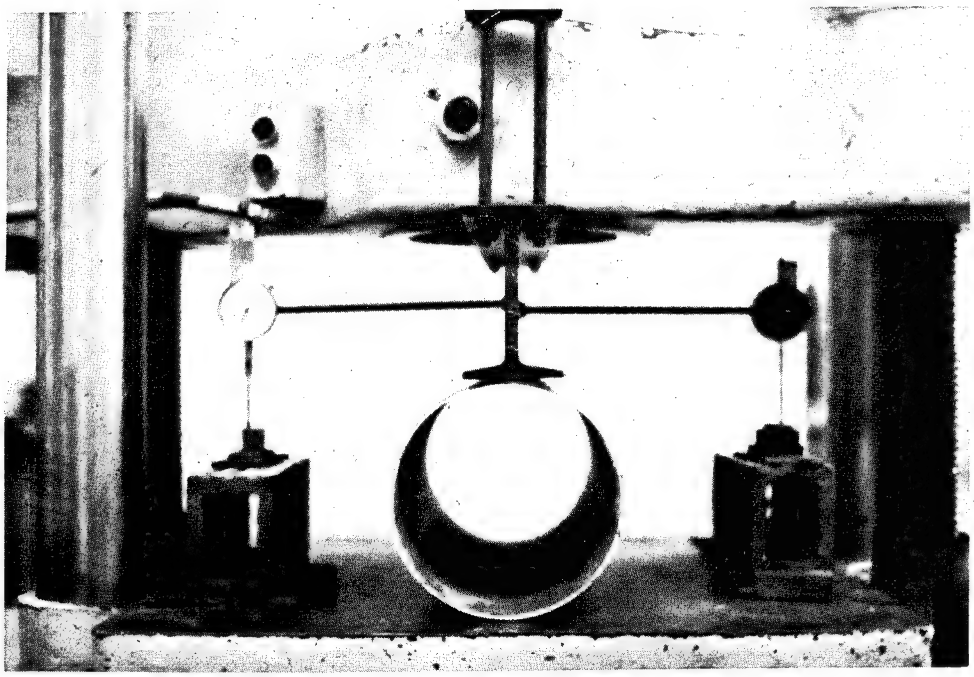


Figure 2. Parallel Plate Apparatus

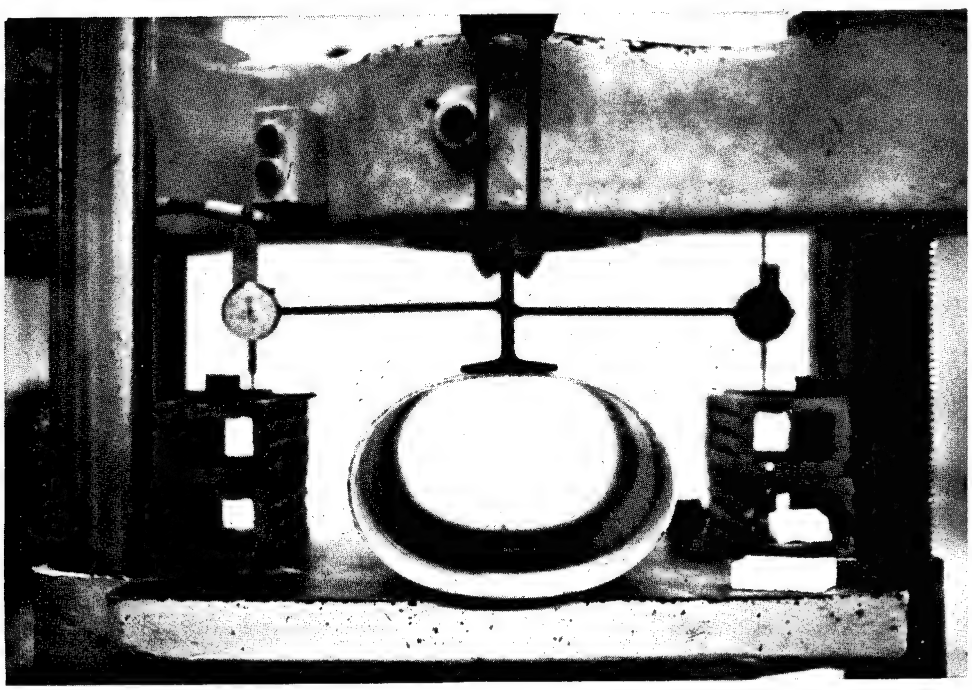


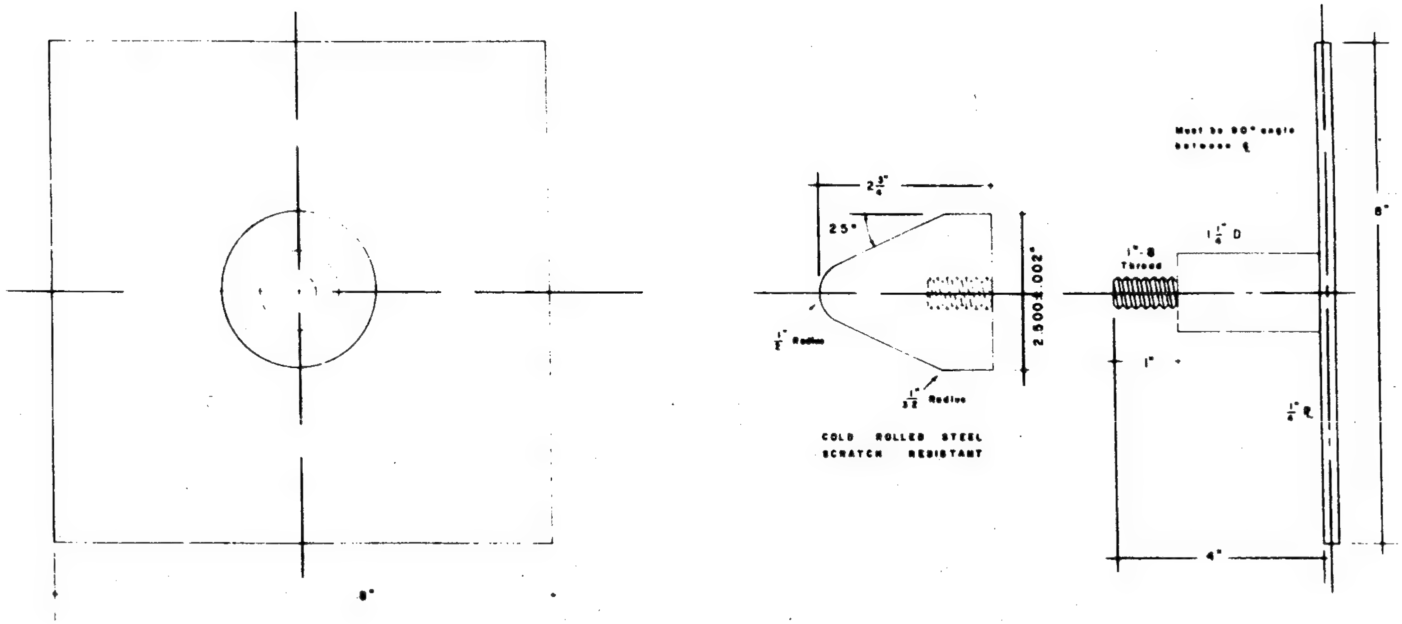
Figure 3. Specimen Being Tested by Parallel Plate Method

hypothetically weakened region is placed at various orientations relative to the loading member to insure a reasonable sampling of pipe strength. The pipe specimen is placed with its axis parallel to beam and it is mounted between the beam and the machine base. Spacers are placed between the machine base and the dial gauge streamers in order to measure the relative deflection of the two parallel plates. The specimen is uniformly loaded at a rate of 600 lbs. per minute and is unloaded when failure, i.e., rupture, occurs or when the deflection exceeds 30% of the original pipe diameter.

Although this test is usually used in studies concerned with earth forces created when the pipe is buried, a feel for the relative stiffness of the various types of pipe is also desirable when water well usage is being considered. The stiffness factor was not calculated because it was not considered of value in water well calculations.

### C. Tup Puncture Test

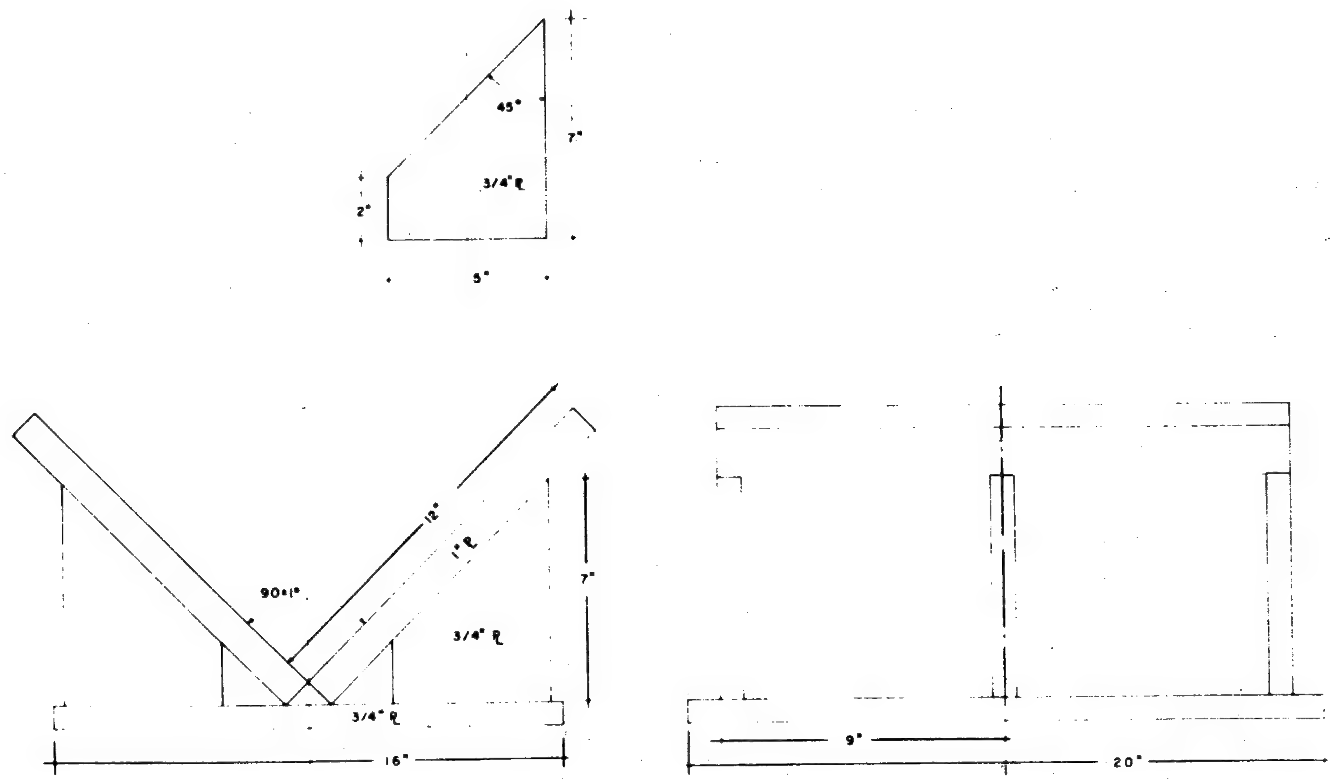
The tup puncture test uses the same basic apparatus suggested by ASTM D2444-67 (see Figure 4). The test method followed by Radian utilizes a constantly applied load instead of the impact load and the vee-block base has been enlarged to accommodate larger specimens as seen in Figure 5. The base is machined so that the two sides of the "vee" form an angle of $90^\circ \pm 0.10^\circ$. The nose of the tup is screwed into a steel mounting rod which is welded perpendicularly to a square steel plate. A collar holding two Federal D81S dial gauges is attached to the tup mounting rod. As in the tension test, the gauges are $180^\circ$ apart. The specimens are measured to determine the point of minimum wall thickness. This hypothetically weakened region is placed at various orientations relative to the loading




CONFIGURATION OF TUP A

Impact resistance of thermoplastic pipe (ASTM D2444)

Figure 4. Tup Test Apparatus




| | | |
|---|---|---|
| 1" X 12" X 18" | 2 Required | 122.4 lbs |
| 3/4" X 16" X 20" | 1 Required | 68.0 lbs |
| 3/4" Trapezoid section | 6 Required | 57.4 lbs |

Figure 5. Vee Block Support

member to insure a reasonable sampling of pipe strength. The nose assembly is placed in the universal load machine and the pipe specimen, with an length/diameter ratio of three, is positioned directly under the nose. Spacers are placed between the dial gauge stems and the base so that the deflection of the tup head vs. load can be measured (see Figures 6 and 7). A uniformly increasing load of 600 lbs. per minute is applied to the specimen through the tapered load head. During loading of the 8-inch specimens, the load at which the first audible weakness occurs is noted. This reference point was discontinued for the 10-inch specimens as the reliability of an audible sound corresponding to a crack in the liner or pipe surface was not considered very accurate.

The deflection of the tup relative to the pipe is monitored during the test to determine the amount of movement that would have taken place with respect to an inner column pipe. When the casing deflection allows its inner surface to make contact with the hypothetical column pipe, the test is stopped.

D. Hydrostatic Collapse

The hydrostatic test simulates the earth forces that act on water well screening. The procedure that is followed in the hydrostatic collapse test is similar to that outlined by E. F. Jacobs and R. A. Sparks[1] in the report they presented at the 21st Annual Meeting of the Reinforced Plastics Division of the Society of the Plastics Industry, Inc. The screen is a strict length to diameter ratio to allow some basis of comparison between the various sizes tested. An length/diameter ratio of three has been used in the hydrostatic tests at Radian.

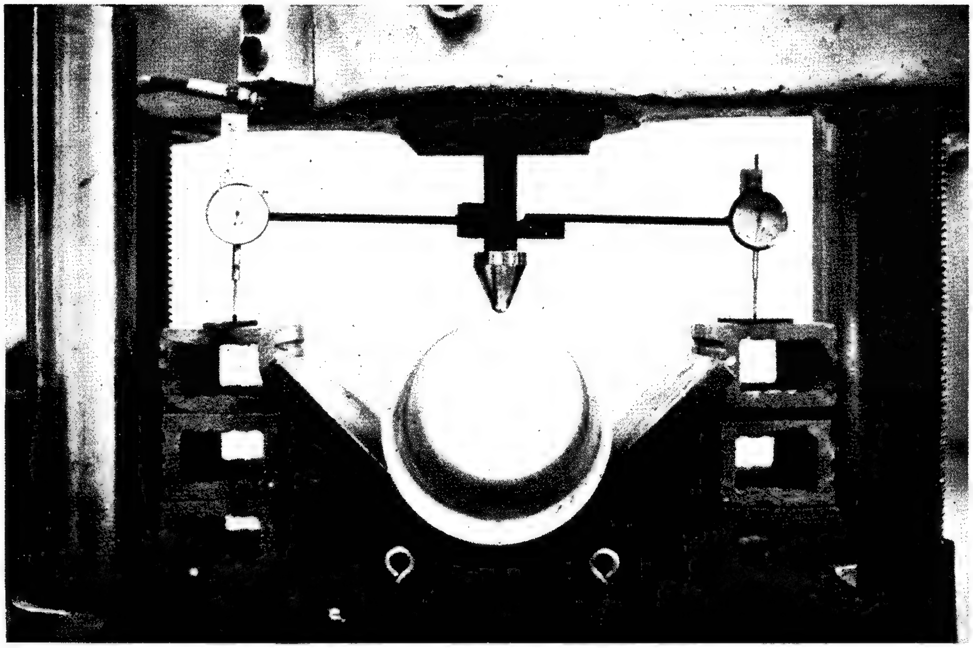


Figure 6. Tup Test Apparatus

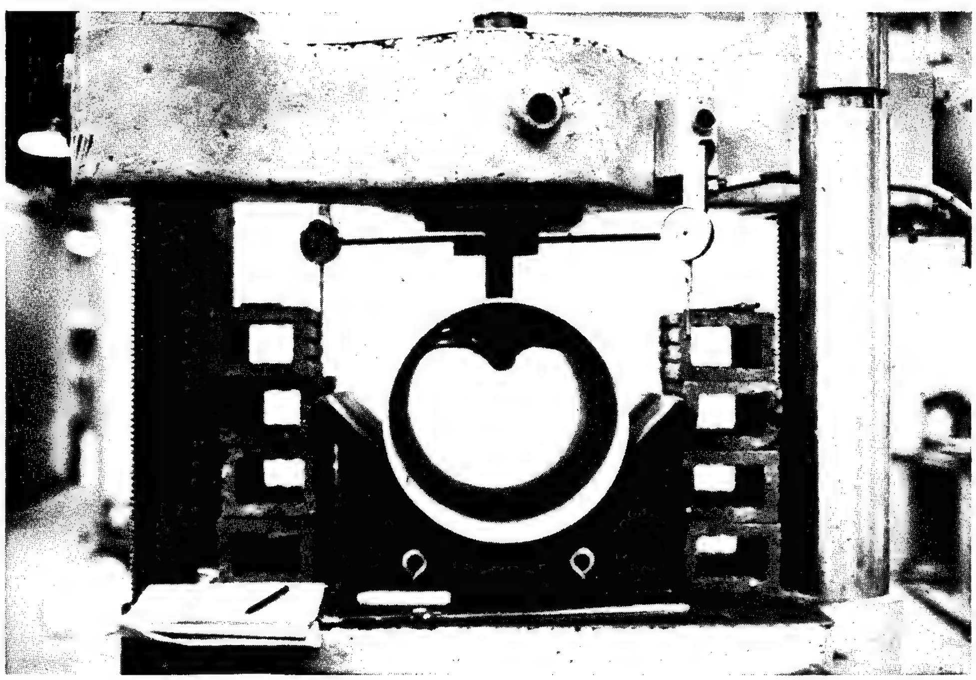
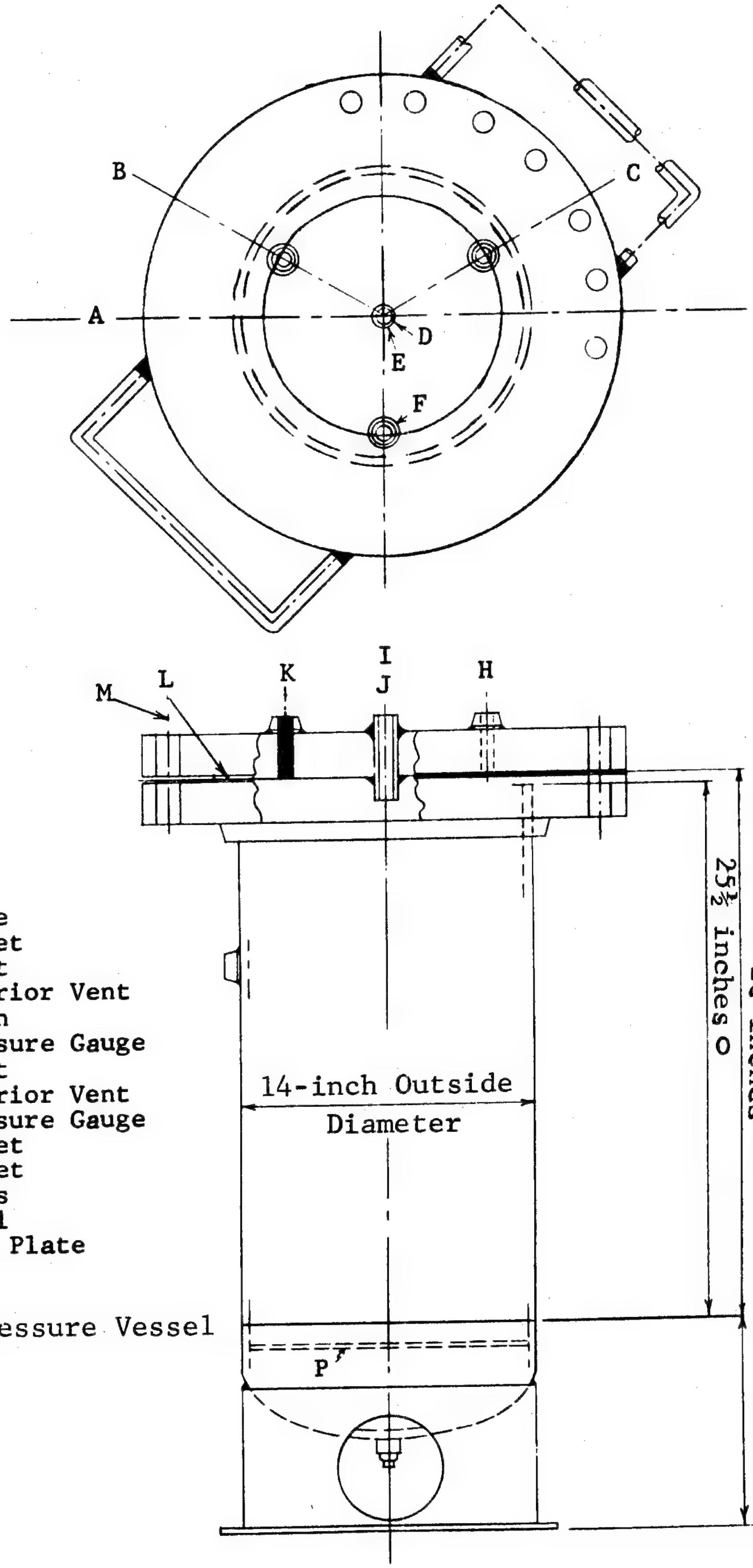


Figure 7. Example of Specimen During Tup Test

Because it is difficult to obtain accurate control of slowly increasing pressure over a large range of pressures, the pressure increase is incremented. Based on the manufacturer's statement of the ultimate external pressure capabilities of the screen, a value of roughly 2/3 the ultimate is used as a starting point. Once the initial pressure is reached it is held for three minutes. From this initial point, steps graduated at approximately 5% of the initial pressure are used with a three minute pause between each step. Since collapse will not necessarily be instantaneous, this pause allows sufficient time for observation of the specimen. A test procedure of this type provides sufficiently accurate data for this test. The pressure medium is water enclosed in a steel pressure tank with compressed nitrogen supplying the pressure on the water. The tank is capable of working pressures up to 575 psig (see Figure 8).

The screen must be watertight in order to function properly in the test apparatus. A layer of thin plastic film is covered by a single layer of Scotch duct tape to provide surface continuity and watertight capabilities without adding strength to the specimens. When the pressure is expected to exceed 100 psig, mylar film is also wrapped around the specimen. These precautions provide a "bridge" over the slots in the screen capable of withstanding the necessary collapse pressures. Vacuum bag sealer (Schnee-Morehead 5110) is used to seal the specimen to the end caps. The end caps create a watertight seal over the open ends of the pipe and, through a connection with the pressure vessel, ensure an atmospheric pressure within the specimen. The pressure exerted on the end caps is carried by an internal structure to ensure that the failure occurs only through radial stresses (see Figure 9).




A - Valve
B=K - Outlet
C=H - Inlet
D=I - Interior Vent
E - Drain
F=J - Pressure Gauge
H=C - Inlet
I=D - Interior Vent
J=F - Pressure Gauge
K=B - Outlet
L - Gasket
M - Studs
O - Shell
P - Base Plate

Figure 8. Pressure Vessel

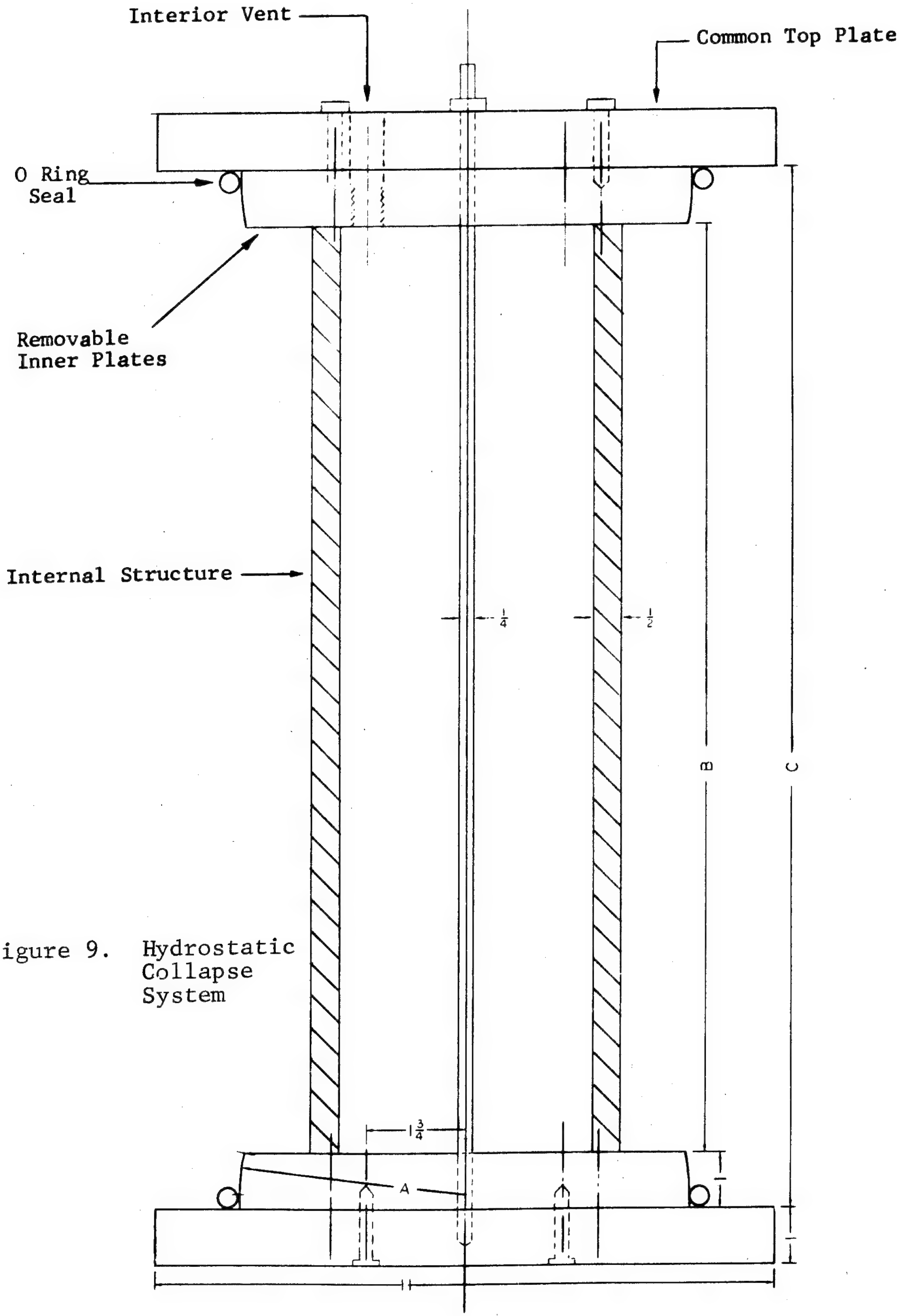



Figure 9. Hydrostatic Collapse System

E. Creep Test

The purpose of the creep test is to determine the "stretch tendency" of the pipe specimen under a set of defined conditions. By relating the test conditions to a real field situation, an approximation of the field performance can be derived that will allow more accurate design in the field.

In order to define the test conditions properly, the creep test must take place in a controlled environment. To ensure consistent conditions, the temperature surrounding the specimens and the physical stresses induced in the specimens, must be carefully monitored and controlled throughout the test period. A test of this type is usually self-regulating because constant supervision by personnel is not practical. The specific criteria used in the design of Radian's creep test for fiberglass reinforced plastic pipe are:

- The capability to sustain large accurate loads.

- The control of the internal environment to $\pm$ 0.1°F and the external environment to $\pm$ 5°F.

To accomplish these goals the following system was designed:

1. Load System - Various methods of load application, including hydraulic, cantilever (moment arm), and spring were considered. A spring system was chosen because smaller errors would be introduced by this method. A frame was designed to put the specimens in axial tension such that each specimen reacts independently of the frame and the other specimens (see Figure 10).

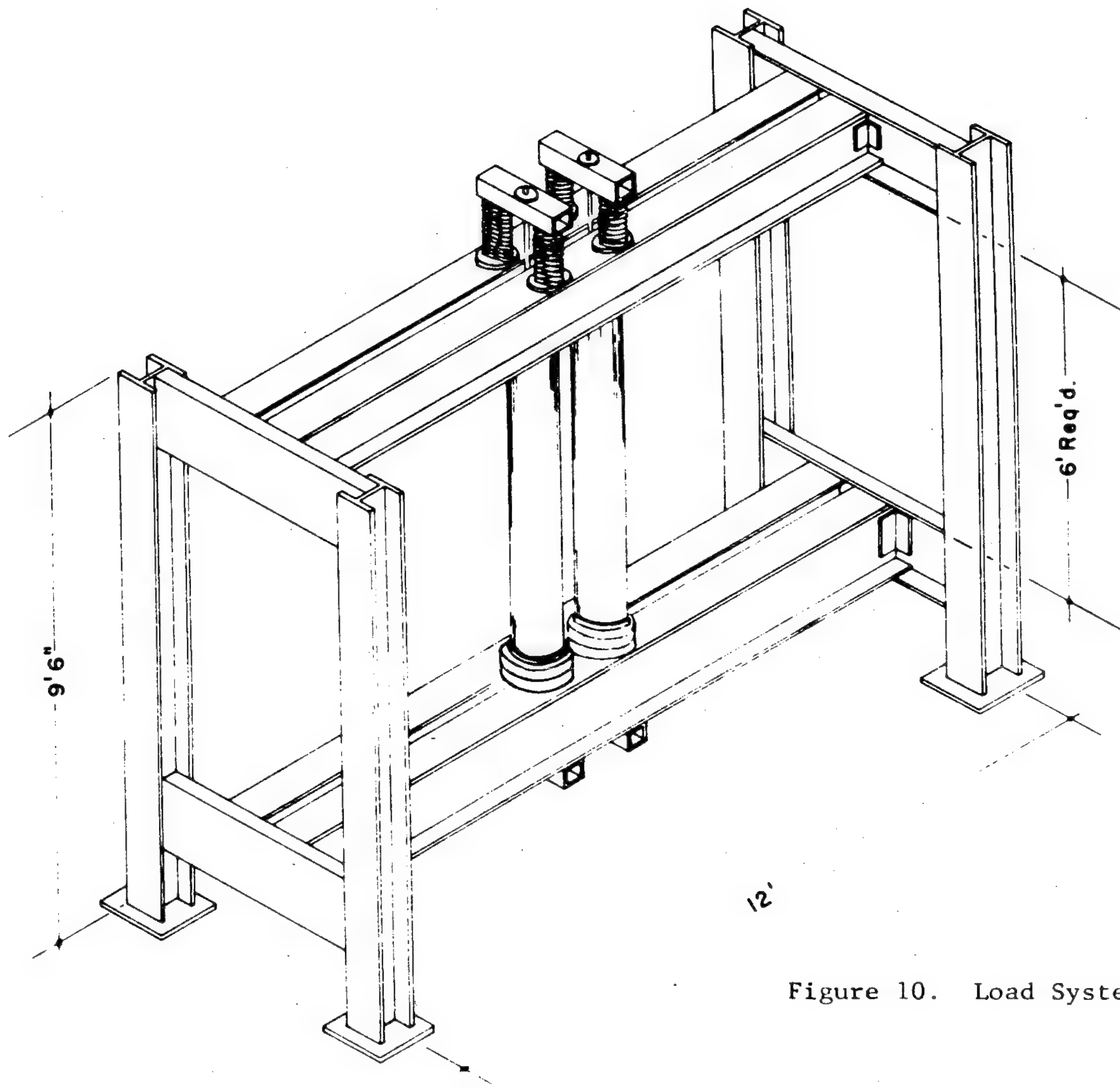



Figure 10.  Load System for Creep Test

The best manner to grip the pipes is to have a pipe-to-loading system interface that does not influence the test results by compromising the pipe material. Using a standard fiberglass flanged connection bolted to a forged steel bind flange, an entirely compatible connection is achieved. A single steel rod is attached to the center of the blind steel flange through which the spring system applies the required load. By using a flanged connection of this type at both ends of the fiberglass specimen, enough flexibility is possible to ensure an axial tension system as is seen in Figure 11.

The elongation of the specimen is measured by the differential movement of two lightweight aluminum yokes attached to the specimen. The yokes contact the pipe through adjustment screws that allow a point contact in two locations. A 40-gauge length is used between the two yokes to minimize possible measurement error. The movement of the pipe is measured by two Federal D81S dial gauges, placed on opposite sides of the top yoke to compensate for any discrete differential movements within the specimen (see Figure 43, page 88).

The above procedure allows an accurate measurement of the specimen performance while allowing each individual specimen to react independently of the frame and from other specimens.

2. Environmental Control - Temperature is an important parameter when considering the small deformations characteristic of creep studies. It is necessary to control this variable as closely as possible so that it can be neglected in data comparisons. To accomplish these goals a system was designed to allow heated water to constantly flow through the interior of the specimens at a temperature of 125°F ± 0.1°F. Heated water is used to enhance the flow characteristics of the plastic in addition to promoting a chemical environment that would more readily attack the resin-glass bond in the fiber matrix. The piping

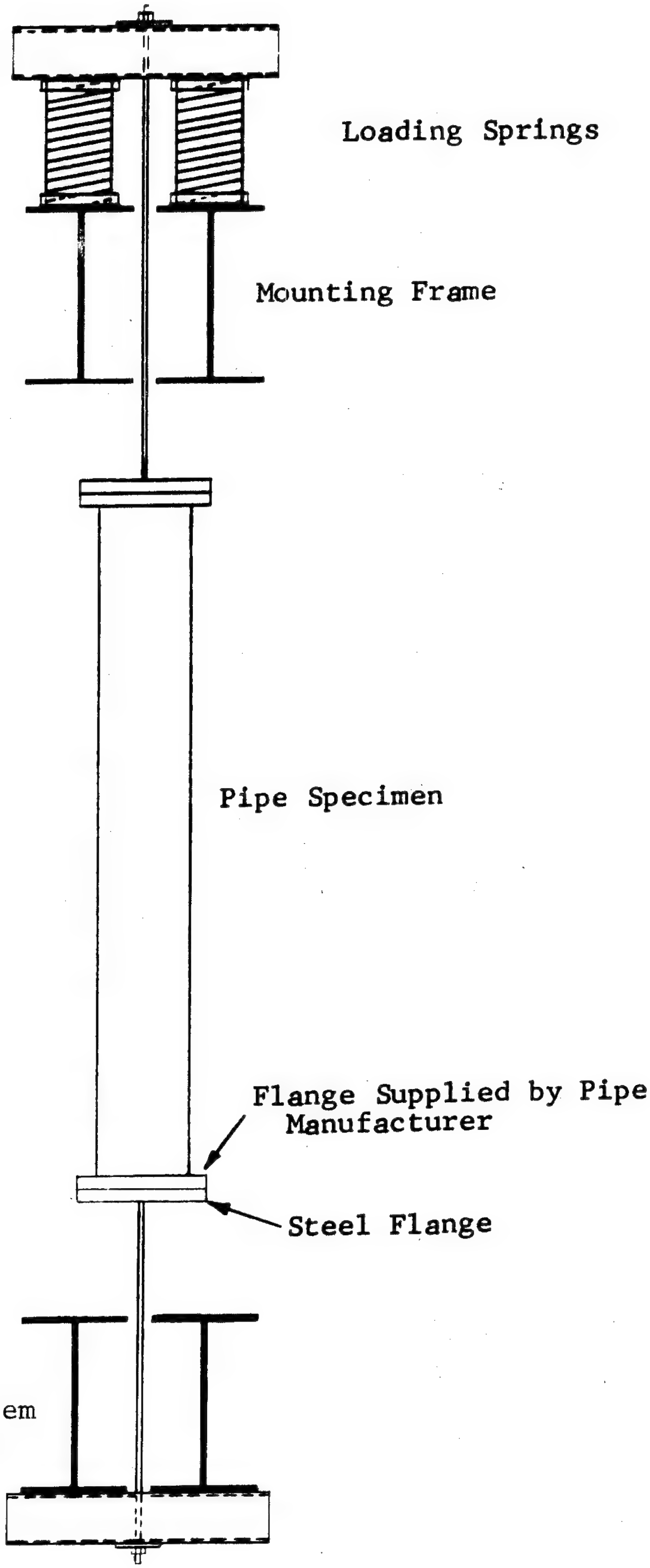



Figure 11. Load System for Creep Test

network consists of 1¼-inch Schedule 40 PVC pipe attached to a 3/4-hp centrifugal pump and arranged to have a closed, recirculating system. All connections were plastic to prevent corrosion and small amounts of sodium sulfite with a cobalt nitrate catalyst were added to the water to remove dissolved oxygen. A 100-gallon fiberglass holding tank houses three immersion type heaters. One 500-watt and one 750-watt heater are run constantly while another 750-watt heater is controlled by a thermoswitch apparatus. The water temperature is monitored at the pump exit and immediately preceding the most distant specimen to allow a constant check on the temperature control system. An orifice is used at the entrance to each specimen to control the amount of water flowing through the individual specimens while the total flow is monitored through a rotameter device. A direct bypass from the pump to the holding tank is utilized in conjunction with the return feed from the specimens to promote a steady water turnover within the holding tank. The tank water level is monitored through a clear plexiglass stand pipe. In case an unexpected or premature failure occurs in the system causing a loss of water, a liquid level switch will shut down the entire system to protect the heaters and preserve as much water as possible.

These two systems provide a reliable and constantly controlled environment to interact with the creep specimens.

## F. Combination Tests

As described in Section III the combination tests combine the tests described above. The tests are run exactly as described in the individual tests except for the following changes:

1. In the creep test followed by a tension test, the previously creeped specimens had to be cut to 24 inches instead of

the 30 inches for the tension tests. This fact is taken into account in the section of data analysis.

2. In the 50% tup load test followed by a creep test, the specimen is subjected to only 50% of the ultimate point load that the pipe can support. The specimen length is 52 inches for both this tup test and the creep test. Before creeping the tupped specimen and puncture is made watertight by gluing a rubber patch over the hole. In this way the pipe is made watertight but the patch does not interfere with testing. All other aspects of the test are the same as described in the individual tests.

3. In the tup test followed by a tension test the length of the specimen is length/diameter = 3 and not always 30 inches as described in the tension test. Therefore, for the 8-inch specimens, 24-inch samples were used as described in the tup test.

## SECTION V

## TEST RESULTS

In the following subsections of this report, the results of the various tests are discussed. These tests were performed in order to compare the physical properties of the various manufacturers' materials and not to make recommendations as to which vendor supplied the superior product. As will be seen from these test results, one pipe will have superior characteristics in one test while another will perform better in another. But, with these data and a knowledge of one's problem, the proper or best material for a particular job can be selected.

### A. Tension Tests

The tensile properties of the fiberglass reinforced plastic pipe are important characteristics of the material and were carefully investigated. Since certain vendors had informed Radian that they had never actually pulled the larger pipe sizes, but calculated their ultimate strength assuming the pipe behaved like a homogeneous material, care was taken to insure quality results. The first difficulty encountered was how to grip the pipe to insure no "end damage" to the tensile specimens. The gripping mechanism utilized by Radian is shown in Figure 1. In using these grips, no "end damage" occurred in the tensile tests.

Tensile tests were conducted on sections of plain end pipe and on the connections used by the various manufacturers.

1. Plain End Pipe

The assembled test fixture for obtaining the tensile data for the plain end pipe specimens is shown in Figure 12. As discussed earlier, the strain gauges were removed shortly before ultimate failure.

Two distinct types of failures occurred in the nine brands of pipe tested by Radian Corporation. The first type was characteristic of filament wound pipe in general, and was identified by a slow tearing of the material along the path of the glass reinforcement as shown in Figure 13. A slip surface preceded the failure and, in some cases, a twisting effect due to the nature of the glass reinforcement direction followed. The pipe samples from A. O. Smith, Amercoat, Koch and Fiberglass Resources followed this pattern and would generally hold a reduced load as the test apparatus continued to tear the specimens apart. The slip surface generally appeared to be about one inch wide and quickly propagated along the longitudinal axis of the pipe specimen from the point of initial slip. Because the slip surface followed the path of winding, a weakened spiral surface was generated allowing the remaining pipe to twist like an extended spring. At this point the slip surface would fail and the pipe would separate in the slip region.

The second type of failure was a sudden, total fracture of the material. The specimens that failed in this manner were the centrifugally cast pipe produced by Fibercast and Apex, the filament wound pipe produced by Brunswick and Ciba, and the contact molded pipe produced by Ceilcoat. All of these companies produce a product with a predominant fiber orientation in the parallel and perpendicular directions with reference to the pipe axis. The Apex pipe differs from all the other pipe tested in that chopped roving is used instead of a continuous filament.

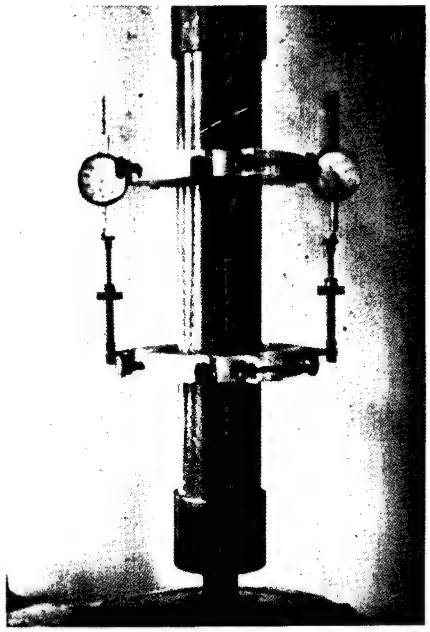


Figure 12. Tension Test Apparatus

Figure 13. Specimen Failed in Axial Tension

The pipe that fails in this sudden manner generally has a failure surface that is perpendicular to the pipe axis. This is reasonable behavior when considering that only the fibers oriented along the longitudinal axis can contribute to the load carrying capabilities of the pipe. The fibers perpendicular to the longitudinal axis cannot influence the axial tension stresses to an extent great enough to cause the type of failure exhibited by a homogeneous material. There was no advance warning of these sudden failures except for the Ceilcoat pipe which exhibited color changes and cracks before failure.

Although it is desirable to have a warning of possible failure in applications where visual checks on the material structure are possible, this fact should not dictate a preference for either type of failure because it is not practical to visually inspect water well pipe after it has been installed. However, the ability to function as a load supporting component after failure may be an advantageous feature.

Some of the fiberglass reinforced pipe that was tested contained an inner surface of resin rich epoxy. This surface lines the inside of the pipe to protect the fiber structure from possible chemical attack. These liners are of various materials and have different thicknesses depending on the individual producer. During the tension tests conducted at Radian, if the pipe in question had a liner, the liner fractured at a low load in comparison to the ultimate strength of the pipe. If the allowable working load recommended by the manufacturer does not exceed the strength of the liner, it is still an active component of the pipe system. However, if the tensile strength of the liner is too closely matched to the allowable pipe load, it may be easily overstressed during well installation by accidental jarring or other mistreatment.

In most cases of lined pipe tested by Radian, the liners failed at approximately the same load regardless of pipe size or manufacturer. An exception is the Ceilcoat liner which is about an eighth of an inch thick and is reinforced by glass. This liner is considered to be an integral part of the load bearing pipe area and is considered to have almost the same modulus of elasticity as in the major fiber area. In this case there was evidence of the cracking in the first layer on each side at loads below the ultimate. Liner failures occurred when approximately 10,000 to 15,000 pounds of load were applied to the pipe. This load range is below the working load capabilities of some of the fiberglass reinforced pipe that was tested. Because some of the products claim to perform reliably when exposed to various chemical environments without the protection of a liner, and because the liners cannot withstand high tensile stresses, it would seem that the addition of a liner is a questionable asset when considering fiberglass reinforced pipe for use in certain applications.

The pipe dimensions are necessary for calculating the various tensile properties of these FRP samples. Table I shows the pipe dimensions measured by Radian on the samples received. Table II shows the dimensions supplied to Radian by the manufacturer. Table III allows a rapid comparison of some of the more important dimensions. As can be seen, there is a discrepancy in some of these measurements. A possible explanation for these discrepancies is that the manufacturers generally specify a minimum wall thickness to the production plant. To make sure that the pipe will pass quality control, the production manager may allow excess material to be added to the pipe. The wall is now heavier than the minimum and satisfies quality control but, when the engineers make their calculations to determine material properties, the specified minimum dimensions may be used in the calculations in place of actual measurements. Erroneous data can easily be obtained in this manner.

## TABLE I

## PIPE DIMENSIONS MEASURED BY RADIAN

| Pipe | Nominal O.D. (in.) | I.D. (in.) | Wall Thickness (in.) | Liner* Thickness (in.) | Total Area (sq. in.) | Fiber Area (sq. in.) |
|---|---|---|---|---|---|---|
| A. O. Smith | 4 | 4.37 | .080 | None | 1.12 | 1.12 |
| | 6 | 6.40 | .111 | None | 2.27 | 2.27 |
| | 8 | 8.34 | .148 | None | 3.95 | 3.95 |
| | 10 | 10.36 | .173 | None | 5.72 | 5.72 |
| Apex | 6 | 6.08 | .270 | .060 | 5.39 | 4.23 |
| | 8 | 7.95 | .329 | .060 | 8.56 | 7.05 |
| | 10 | 9.93 | .402 | .060 | 13.1 | 11.2 |
| Bondstrand | 4 | 4.15 | .207 | .020 | 2.84 | 2.58 |
| | 6 | 6.27 | .206 | .020 | 4.19 | 3.82 |
| | 8 | 8.23 | .246 | .020 | 6.55 | 6.03 |
| | 10 | 10.36 | .250 | .020 | 8.33 | 7.71 |
| Brunswick | 8 | 8.04 | .195 | None | 5.04 | 5.04 |
| | 10 | 10.05 | .187 | None | 6.01 | 6.01 |
| Ceilcoat | 4 | 4.00 | .275 | .125 | 3.69 | 3.69 |
| | 6 | 6.01 | .283 | .125 | 5.59 | 5.59 |
| | 8 | 8.02 | .386 | .125 | 10.2 | 10.2 |
| | 10 | 10.03 | .438 | .125 | 14.4 | 14.4 |
| Ciba | 4 | 4.35 | .090 | .015-.025 | 1.28 | 1.08 |
| | 6 | 6.39 | .120 | .015-.025 | 2.45 | 2.15 |
| Fibercast | 4 | 3.88 | .308 | .060 | 4.06 | 3.32 |
| | 6 | 5.98 | .320 | .060 | 6.33 | 5.19 |
| | 8 | 8.00 | .315 | .060 | 8.23 | 6.71 |
| Fiberglass Resources | 4 | 4.38 | .170 | .0075 | 2.43 | 2.33 |
| | 6 | 6.44 | .136 | .015 | 2.81 | 2.51 |
| | 8 | 8.40 | .247 | .015 | 6.71 | 6.31 |
| | 10 | 10.44 | .208 | .015 | 6.96 | 6.46 |
| Koch | 4 | 4.37 | .085 | None | 1.19 | 1.19 |
| | 6 | 6.44 | .092 | None | 1.89 | 1.89 |
| | 8 | 8.27 | .140 | None | 3.69 | 3.69 |

* Not measured, supplied by manufacturer.

# TABLE II

## DATA COMPILED FROM THE MANUFACTURERS

| Pipe | | Pounds Per Ft. | Ultimate Axial Strength | Recommended Operating Data @ 80°F | Tensile Modulus of Elasticity | Burst Pressure | External Collapse Pressure | Inside Diameter (in) | O.D. (in) | Wall Thickness (in) | Liner Thickness (in) | Maximum Operating Temperature | Ultimate Elongation | Type of Resin | Type of Manufacturing |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A. O. Smith | | | | | | | | | | | | | | | |
| Red Thread | 4" | 0.4 | 9,100 psi | 2,200 Lbs Tension | $1.15 \times 10^6$ psi | 1900 psi | 38 psi | 4.360 | 4.500 | .070 | -- | 150°F | 2% | epoxy | Filament wound with a 54 3/4° angle of |
| Red Thread | 6" | 1.7 | 9,100 psi | 6,100 Lbs Tension | $1.15 \times 10^6$ psi | - | - | 6.405 | 6.625 | .110 | -- | 150°F | 2% | epoxy | wind |
| Red Thread | 8" | 3.0 | 9,100 psi | 7,600 Lbs Tension | $1.15 \times 10^6$ psi | - | - | 8.352 | 8.632 | .126 | -- | 150°F | 2% | epoxy | |
| Red Thread | 10" | 4.7 | 9,100 psi | 13,200 Lbs Tension | $1.15 \times 10^6$ psi | - | - | 10.350 | 10.70 | .156 | -- | 150°F | 2% | epoxy | |
| Apex | | | | | | | | | | | | | | | |
| A-382 150 psi | 6" | 3.6 | 10,000 psi | - | - | - | - | | 6.625 | .248 | .040-.060 | 200°F | - | polyester | Centrifugally cast with 1" chopped fibers |
| A-382 150 psi | 8" | 6.2 | 10,000 psi | - | - | - | - | | 8.625 | .323 | .040-.060 | 200°F | - | polyester | 3/4 of them oriented longitudinally and |
| A-382 150 psi | 10" | 9.2 | 10,000 psi | - | - | - | - | | 10.750 | .399 | .040-.060 | 200°F | - | polyester | 1/4 oriented on hoop |
| Bondstrand | | | | | | | | | | | | | | | |
| Series 2000 | 4" | 1.9 | 16,750 psi | 4,500 psi Tension | $2.3 \times 10^6$ psi | - | - | 4.16 | 4.5 | .180 | .020 | 300°F | - | epoxy | Filament wound |
| Series 2000 | 6" | 3.0 | 16,750 psi | 4,500 psi Tension | $2.3 \times 10^6$ psi | - | - | 6.265 | 6.625 | .180 | .020 | 300°F | - | epoxy | |
| Series 2000 | 8" | 4.0 | 16,750 psi | 4,500 psi Tension | $2.3 \times 10^6$ psi | - | - | 8.225 | 8.625 | .200 | .020 | 300°F | - | epoxy | |
| Series 2000 | 10" | 5.5 | 16,750 psi | 4,500 psi Tension | $2.3 \times 10^6$ psi | - | - | 10.350 | 10.75 | .200 | .020 | 300°F | - | epoxy | |
| Brunswick | | | | | | | | | | | | | | | |
| | 8" | 4.1 | 62,000 lbs | 15,300 lbs Tension | $2.2 \times 10^6$ psi | - | - | 8.04 | 8.40 | .180-.200 | -- | 165°F | 2.5% | epoxy | Filament wound |
| | 10" | 5.1 | 72,000 lbs | 18,000 lbs Tension | $2.2 \times 10^6$ psi | - | - | 10.04 | 10.40 | .180-.200 | -- | 165°F | 2.5% | epoxy | |
| Ceilcoat | | | | | | | | | | | | | | | |
| Duracor 1000-9A | 4" | 2.2 | 12,000 psi | 100 psi Service<br>1,500 psi Tension | $9.2 \times 10^5$ psi | 800-1,000 psi | Full Vacuum | 4.00 | - | 1/4 | .125 | 160°F | 1.3% | polyester | Contact molded with 25% glass by weight |
| Duracor 1000-9A | 6" | 3.2 | 12,000 psi | 100 psi Service<br>1,500 psi Tension | $9.2 \times 10^5$ psi | 800-1,000 psi | Full Vacuum | 6.00 | - | 3/8 | .125 | 160°F | 1.3% | polyester | |
| Duracor 1000-9A | 8" | 5.3 | 12,000 psi | 100 psi Service<br>1,500 psi Tension | $9.2 \times 10^5$ psi | 800-1,000 psi | Full Vacuum | 8.00 | - | 7/16 | .125 | 160°F | 1.3% | polyester | |
| Duracor 1000-9A | 10" | 8.0 | 12,000 psi | 100 psi Service<br>1,500 psi Tension | $9.2 \times 10^5$ psi | 800-1,000 psi | Full Vacuum | 10.00 | - | 1/2 | .125 | 160°F | 1.3% | polyester | |
| Ciba | | | | | | | | | | | | | | | |
| Dualoy 2000 | 4" | .8 | 25,000 lbs | 6,200 lbs Tension | $2.7 \times 10^6$ psi | 2,250 psi | 55 psi | 4.360 | 4.500 | .07 | .015-.025 | 200°F | 3.8% | epoxy | Dual angle filament wound |
| Dualoy 2000 | 6" | 1.7 | 60,000 lbs | 15,000 lbs Tension | $2.7 \times 10^6$ psi | 2,200 psi | 55 psi | 6.625 | 6.405 | .11 | .015-.025 | 200°F | 3.8% | epoxy | |
| Fibercast | | | | | | | | | | | | | | | |
| CR-3040 | 4" | 2.90 | 79,870 lbs | 9,000 lbs Tension | $1.5 \times 10^6$ psi | 3,000 psi | - | 3.900 | 4.500 | .30 | .060 | 300°F | - | epoxy | Centrifugally cast |
| RB-2530 | 6" | 4.15 | 119,525 lbs | 13,000 lbs Tension | $1.5 \times 10^6$ psi | 2,800 psi | - | 6.025 | 6.625 | .30 | .060 | 300°F | - | epoxy | |
| RB-2530 | 8" | 5.40 | 156,850 lbs | 17,000 lbs Tension | $1.5 \times 10^6$ psi | 1,600 psi | - | 8.025 | 8.625 | .30 | .060 | 300°F | - | epoxy | |
| Fiberglass Resources | | | | | | | | | | | | | | | |
| Kwi Key | 4" | 1.8 | 9,000 psi min | 5,250 lbs Tension | $1.35 \times 10^6$ psi | - | - | 4.200 | 4.500 | .150 | .0075 | 150°F | - | epoxy | Filament wound with a 54 3/4° angle of |
| Kwi Key | 6" | 2.6 | 9,000 psi min | 11,400 lbs Tension | $1.35 \times 10^6$ psi | - | - | 6.325 | 6.625 | .150 | .015 | 150°F | - | epoxy | wind |
| Kwi Key | 8" | 4.8 | 9,000 psi min | 350 psi pressure | $1.35 \times 10^6$ psi | - | - | 8.265 | 8.625 | .180 min | .015 | 150°F | - | epoxy | |
| Kwi Key | 10" | 5.9 | 9,000 psi min | 350 psi pressure | $1.35 \times 10^6$ psi | - | - | 10.39 | 10.750 | .180 min | .015 | 150°F | - | epoxy | |
| Koch | | | | | | | | | | | | | | | |
| Blue Streak | 4" | 0.9 | 9,250 psi | 300 psi pressure | $1.5 \times 10^6$ psi | 1,500 psig | 35 psig | 4.36 | 4.5 | .09 | -- | 200°F | 2% | epoxy | Filament wound |
| Blue Streak | 6" | 1.8 | 9,250 psi | 300 psi pressure | $1.5 \times 10^6$ psi | 1,400 psig | 20 psig | 6.43 | 6.625 | .11 | -- | 200°F | 2% | epoxy | |
| Blue Streak | 8" | 2.0 | 9,250 psi | 225 lbs pressure | $1.5 \times 10^6$ psi | 1,275 psig | >20 psig | | 8.50 | .142 | -- | 200°F | - | epoxy | |

TABLE III

COMPARISON OF DATA SUPPLIED BY MANUFACTURERS AND DATA MEASURED BY RADIAN CORPORATION

| Pipe | Nominal O.D. (in.) | Inside Diameter (in.) | | Wall Thickness (in.) | | Ultimate Axial Strength | |
|---|---|---|---|---|---|---|---|
| | | Man. | Radian | Man. | Radian | Manufacturer | Radian |
| A. O. Smith | 4 | 4.36 | 4.37 | .070 | .080 | 9,100 psi | 7,660 psi |
| | 6 | 6.40 | 6.40 | .110 | .110 | 9,100 psi | 8,630 psi |
| | 8 | 8.35 | 8.34 | .126 | .148 | 9,100 psi | 9,460 psi |
| | 10 | 10.35 | 10.36 | .156 | .173 | 9,100 psi | 8,910 psi |
| Apex | 6 | 6.13 | 6.08 | .248 | .270 | 10,000 psi | 6,740 psi |
| | 8 | 7.98 | 7.95 | .323 | .329 | 10,000 psi | 7,530 psi |
| | 10 | 9.95 | 9.93 | .399 | .402 | 10,000 psi | 7,880 psi |
| Bondstrand | 4 | 4.14 | 4.15 | .180 | .207 | 16,750 psi | 9,110 psi |
| | 6 | 6.27 | 6.27 | .180 | .206 | 16,750 psi | 14,100 psi |
| | 8 | 8.23 | 8.23 | .200 | .246 | 16,750 psi | 9,490 psi |
| | 10 | 10.35 | 10.36 | .200 | .250 | 16,750 psi | 9,280 psi |
| Brunswick | 8 | 8.04 | 8.04 | .180-.200 | .195 | 62,00C lbs | 80,800 lbs |
| | 10 | 10.04 | 10.05 | .180-.200 | .187 | 72,000 lbs | 98,350 lbs |
| Ceilcoat | 4 | 4.00 | 4.00 | .250 | .275 | 12,000 psi | 7,990 psi |
| | 6 | 6.00 | 6.01 | .375 | .283 | 12,000 psi | 10,800 psi |
| | 8 | 8.00 | 8.02 | .438 | .386 | 12,000 psi | 8,970 psi |
| | 10 | 10.00 | 10.03 | .500 | .438 | 12,000 psi | 7,360 psi |
| Ciba | 4 | 4.36 | 4.35 | .07 | .090 | 25,000 lbs | 36,000 lbs |
| | 6 | 6.63 | 6.39 | .11 | .120 | 60,000 lbs | 67,900 lbs |
| Fibercast | 4 | 3.90 | 3.88 | .300 | .308 | 79,870 lbs | 62,567 lbs |
| | 6 | 6.03 | 5.98 | .300 | .320 | 119,525 lbs | 93,100 lbs |
| | 8 | 8.03 | 8.00 | .300 | .315 | 156,850 lbs | 122,000 lbs |
| Fiberglass Resources | 4 | 4.20 | 4.38 | .150 | .170 | 9,000 psi | 10,400 psi |
| | 6 | 6.33 | 6.44 | .150 | .136 | 9,000 psi | 9,050 psi |
| | 8 | 8.27 | 8.40 | .180 min | .247 | 9,000 psi | 8,140 psi |
| | 10 | 10.39 | 10.44 | .180 min | .208 | 9,000 psi | 9,740 psi |
| Koch | 4 | 4.36 | 4.37 | .09 | .085 | 9,250 psi | 10,100 psi |
| | 6 | 6.43 | 6.44 | .11 | .092 | 9,250 psi | 7,940 psi |
| | 8 | 8.22 | 8.27 | .142 | .140 | 9,250 psi | 8,810 psi |

Most of the pipes tested behaved similarly to an inelastic material. In some of the initial tests, a large load was placed on the pipe and then released before the pipe failed. Upon reloading, the specimen was not capable of reaching the previous load before it failed. This test was run on a few extra specimens and may indicate a characteristic effect of fiberglass pipe similar to the hysteresis effect, but without the benefit of regaining the highest previously stressed condition.

The load-strain, not stress-strain, curves for the 4-, 6-, 8-, and 10-inch diameter pipe made by A. O. Smith and Apex are shown in Figures 14 and 15. Similar curves for Bondstrand, Ceilcoat, Ciba, Brunswick, Fibercast, Fiberglass Resources and Koch pipe are shown in Figures 16 through 22. It is of interest to note that the 6-inch specimens from Fiberglass Resources, Figure 21, have a lower ultimate strength than the 4-inch specimen. This may be because the 4-inch sample has the thickest wall (see Table I).

A load-strain curve has been used instead of the customary stress-strain curve because of the nature of FRP construction. Stress is a common term used in reference to homogeneous materials, but, in the case of FRP, it is difficult to identify a real value for stress without also saying where that stress acts. The stress level is different within the resin used to bind the glass fibers to the pipe than it is in the glass itself.

For continuous filament composite materials with uniaxial reinforcement the strength is computed by

$$\sigma_c = \sigma_f V_v + \sigma_m V_m$$

$$E_c = E_f V_f + E_m V_m$$

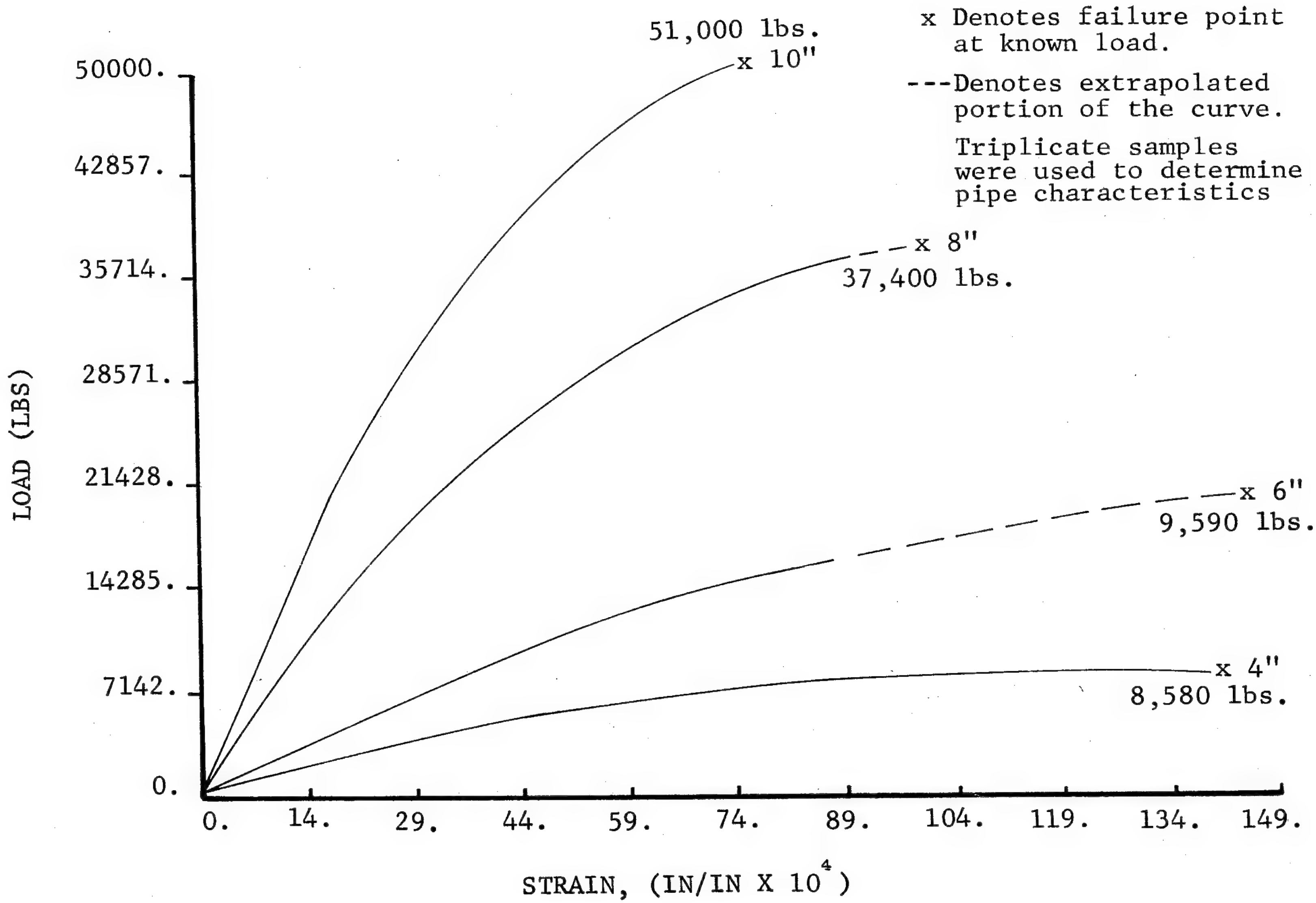



Figure 14. Tension Test A. O. Smith

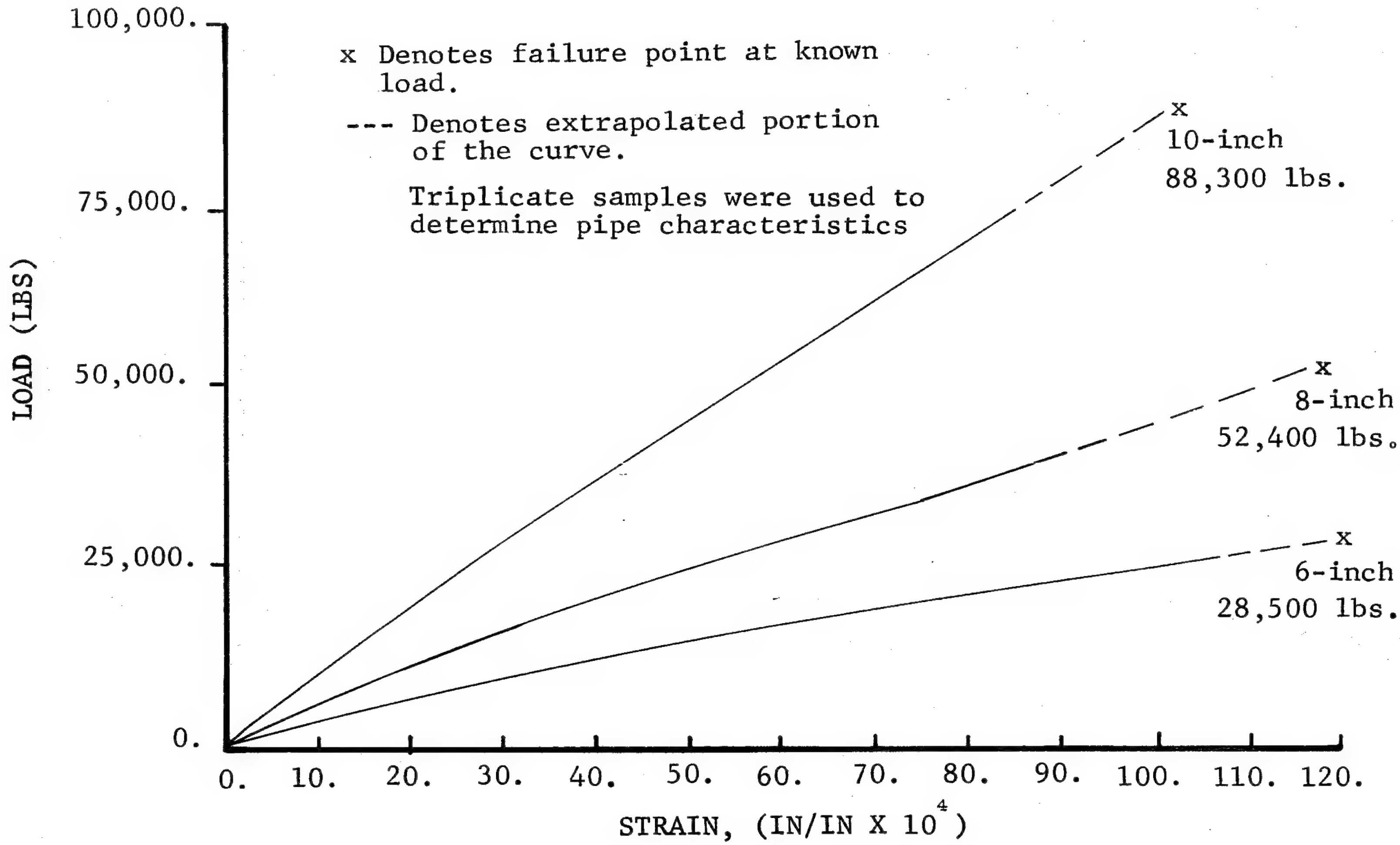



Figure 15. Tension Test Apex

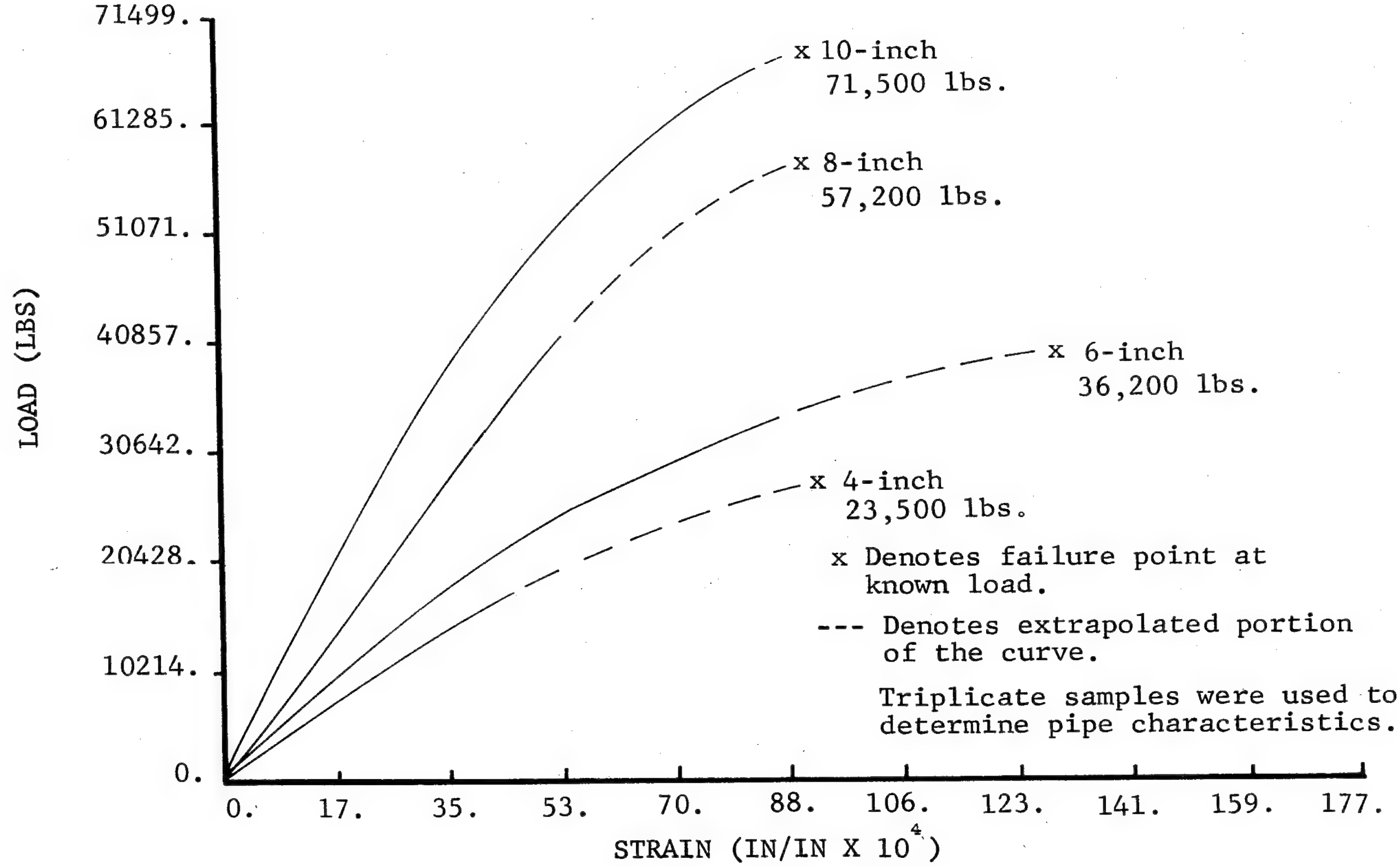



Figure 16. Tension Test Bondstrand

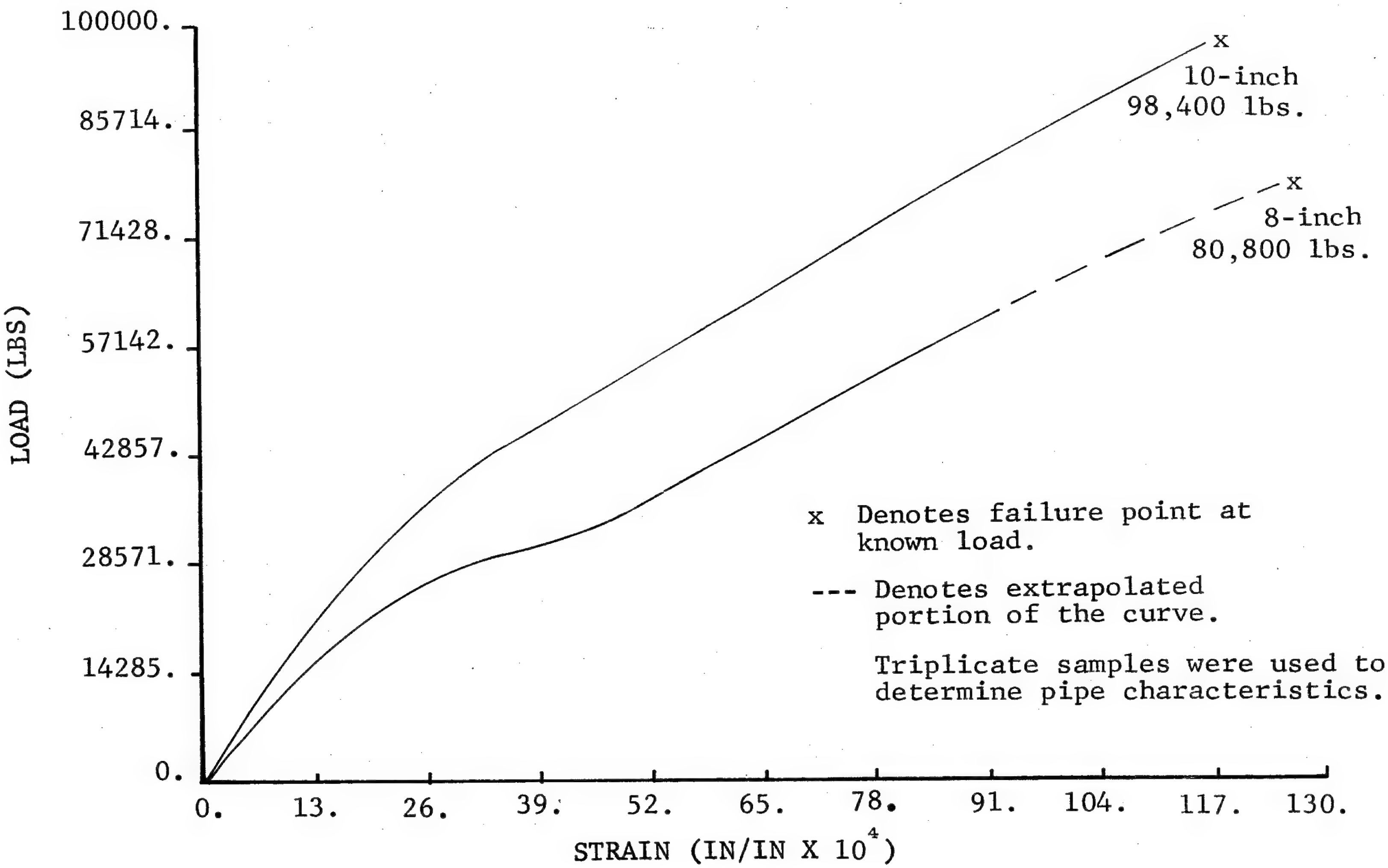



Figure 17. Tension Test Brunswick

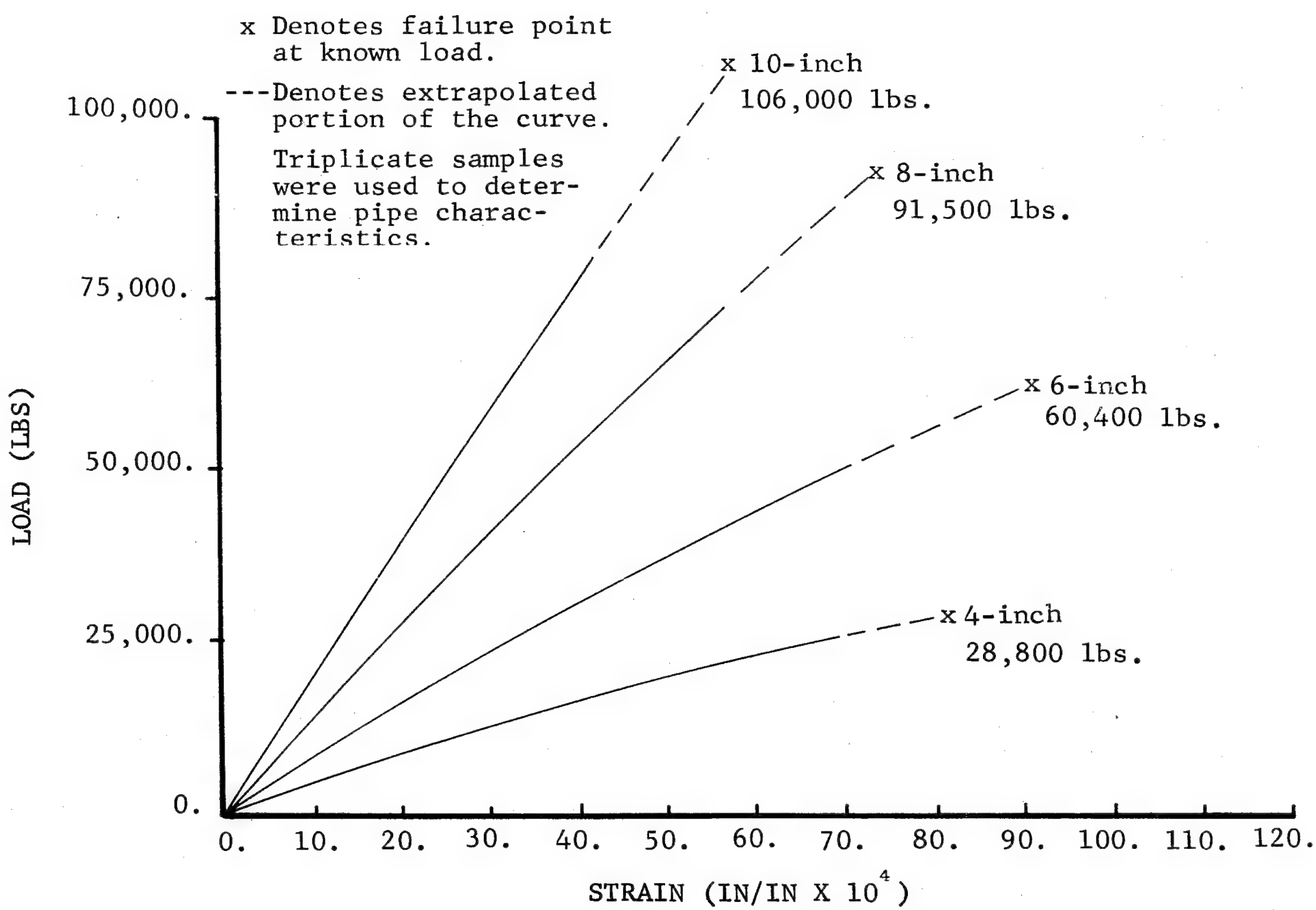



Figure 18. Tension Test Ceilcoat

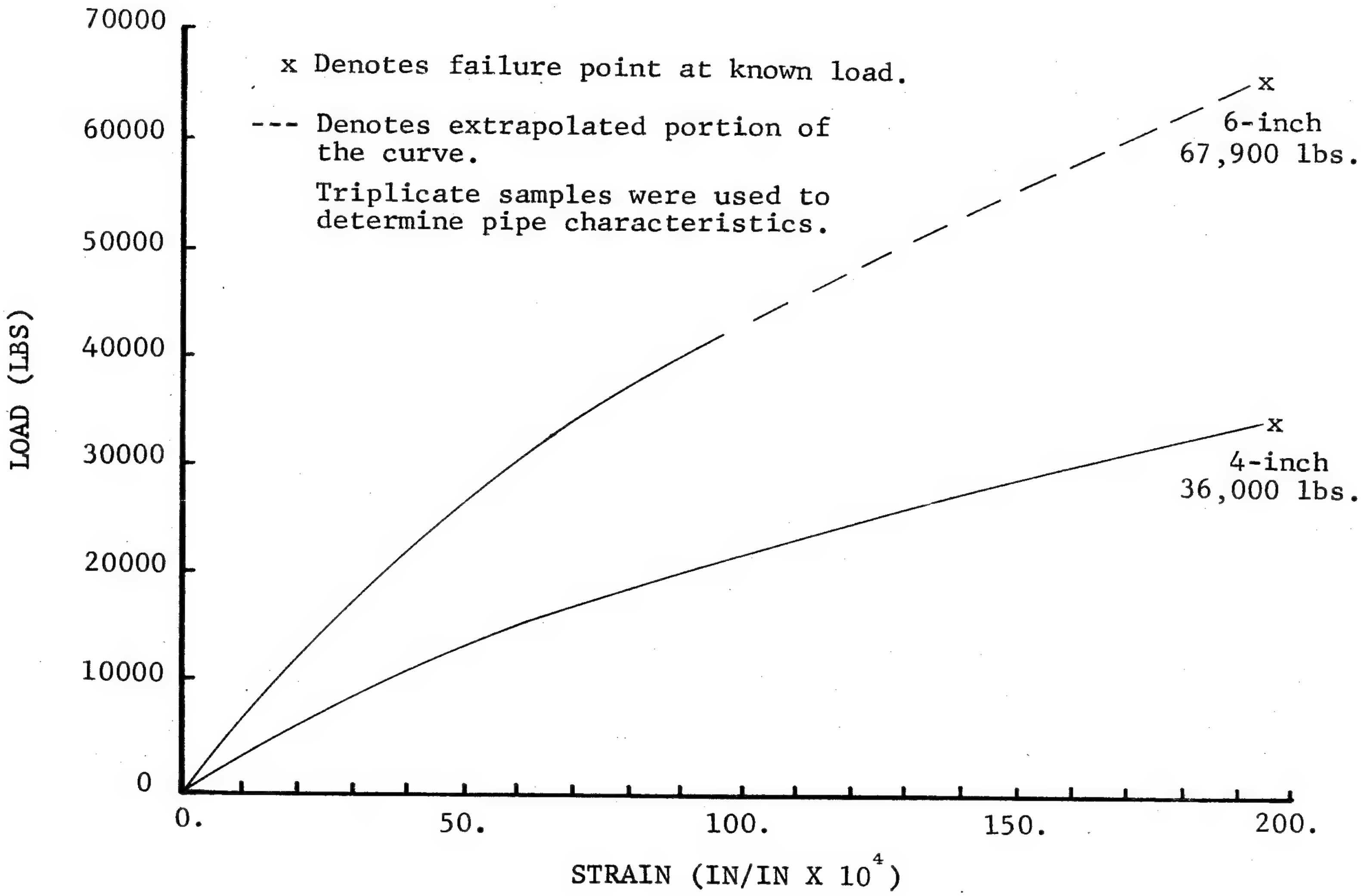



Figure 19. Tension Test Ciba

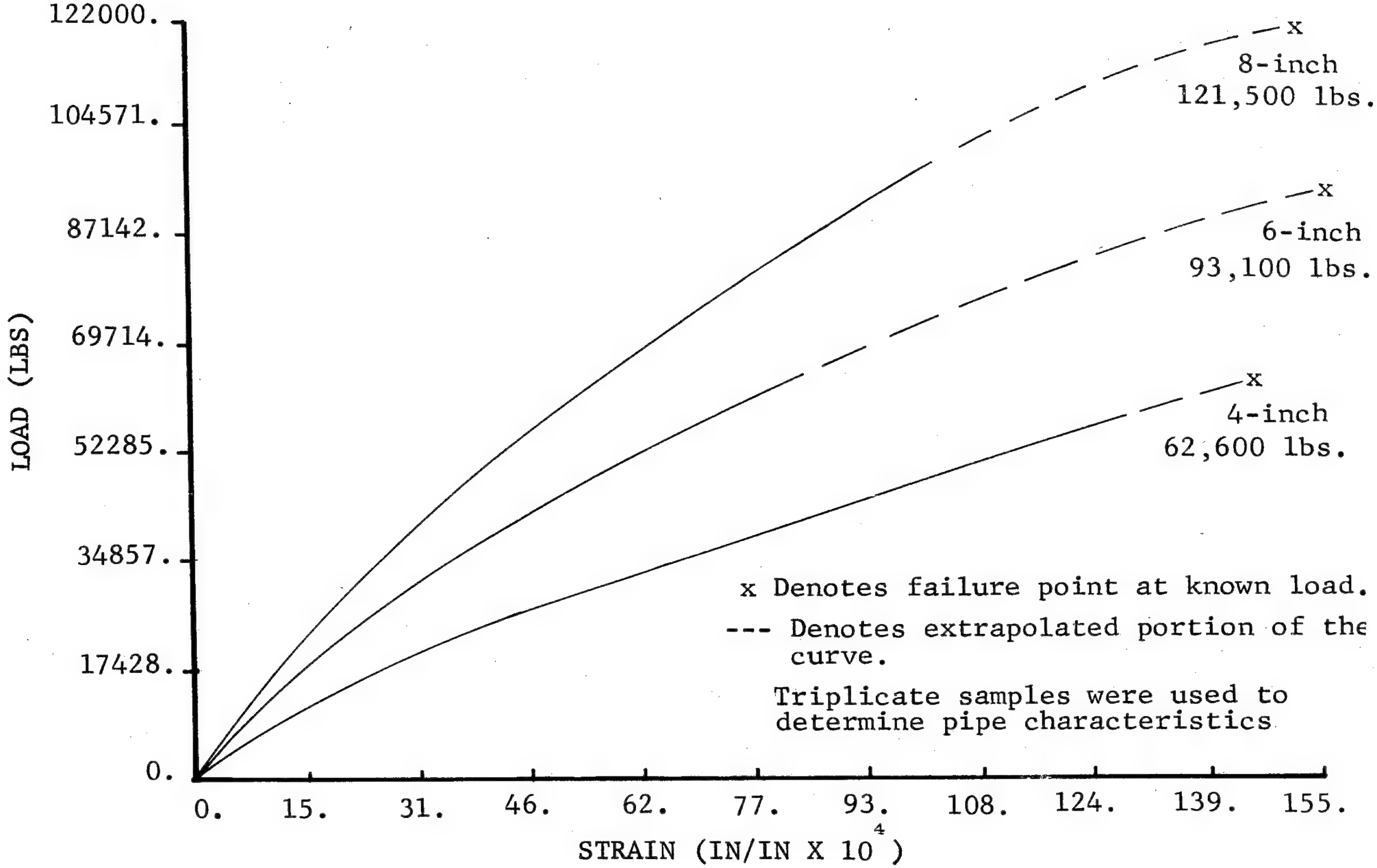



Figure 20. Tension Test Fibercast

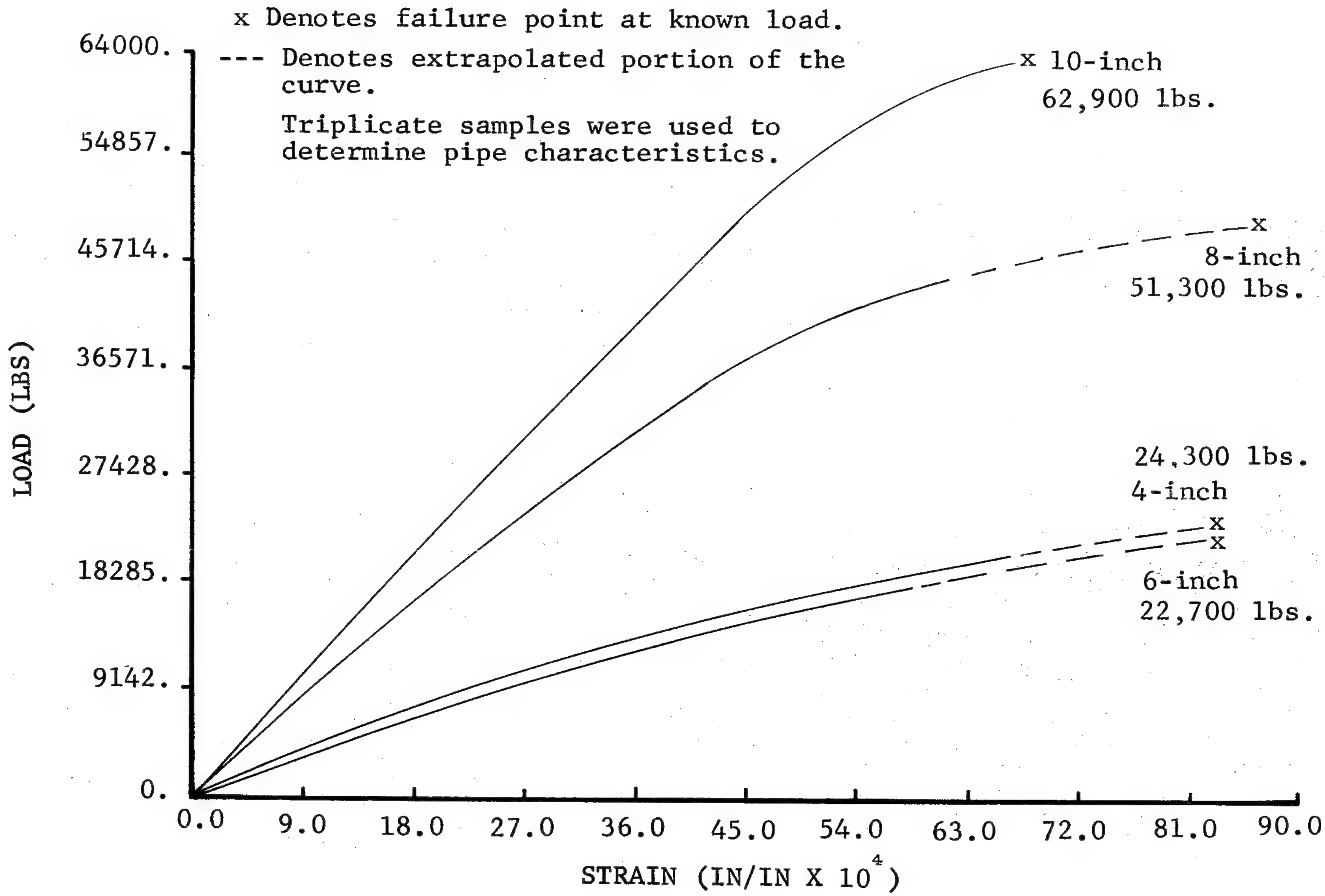



Figure 21. Tension Test Fiberglass Resources

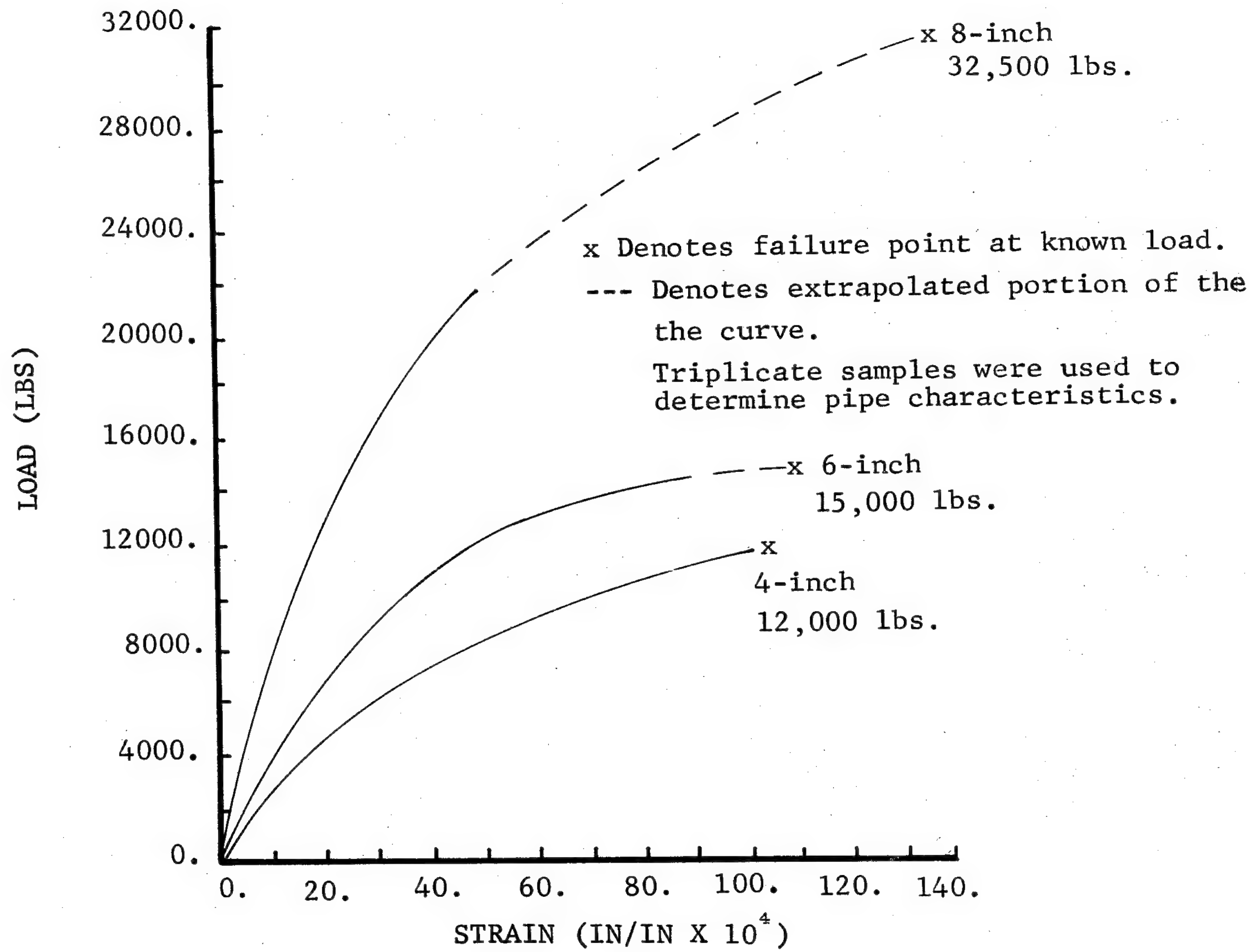



Figure 22. Tension Test Koch

where $E$ = modulus

$\sigma$ = stress

$v$ = volume fraction

$f$ = fiber

$m$ = matrix

$c$ = composite

For the case where the fibers are oriented on angles the modulus value is between values calculated for the longitudinal and traverse directions of a unidirectional composite[2]. Other expressions have been derived for the strength and modulus of short fiber composites. Form this formula it can be seen that the properties of the pipe tested can drastically be altered merely by changing the angle of wind. On Figures 23 and 24 this property can be seen. The Ciba pipe has fibers oriented parallel to the pipe's major axis. For comparable fiber areas the Ciba pipe is very strong in tension.

Although stress values can allow relative comparisons if they are all calculated the same way, the actual value is fictitious in theory. However, as long as the same construction, e.g., the same fiber orientation and same weight percent glass are used the stress on the composite material remains fairly constant (Table III). In order to compare the actual strengths of different brands of pipe, Radian has used the actual value, the known load in place of a computed stress value.

Figures 25 and 26 compare the load-strain curves for pipe of the same nominal diameter of the various manufacturers.

The ultimate strength reported by the manufacturers and the ultimate strength obtained by the above tests are also compared in Table III.

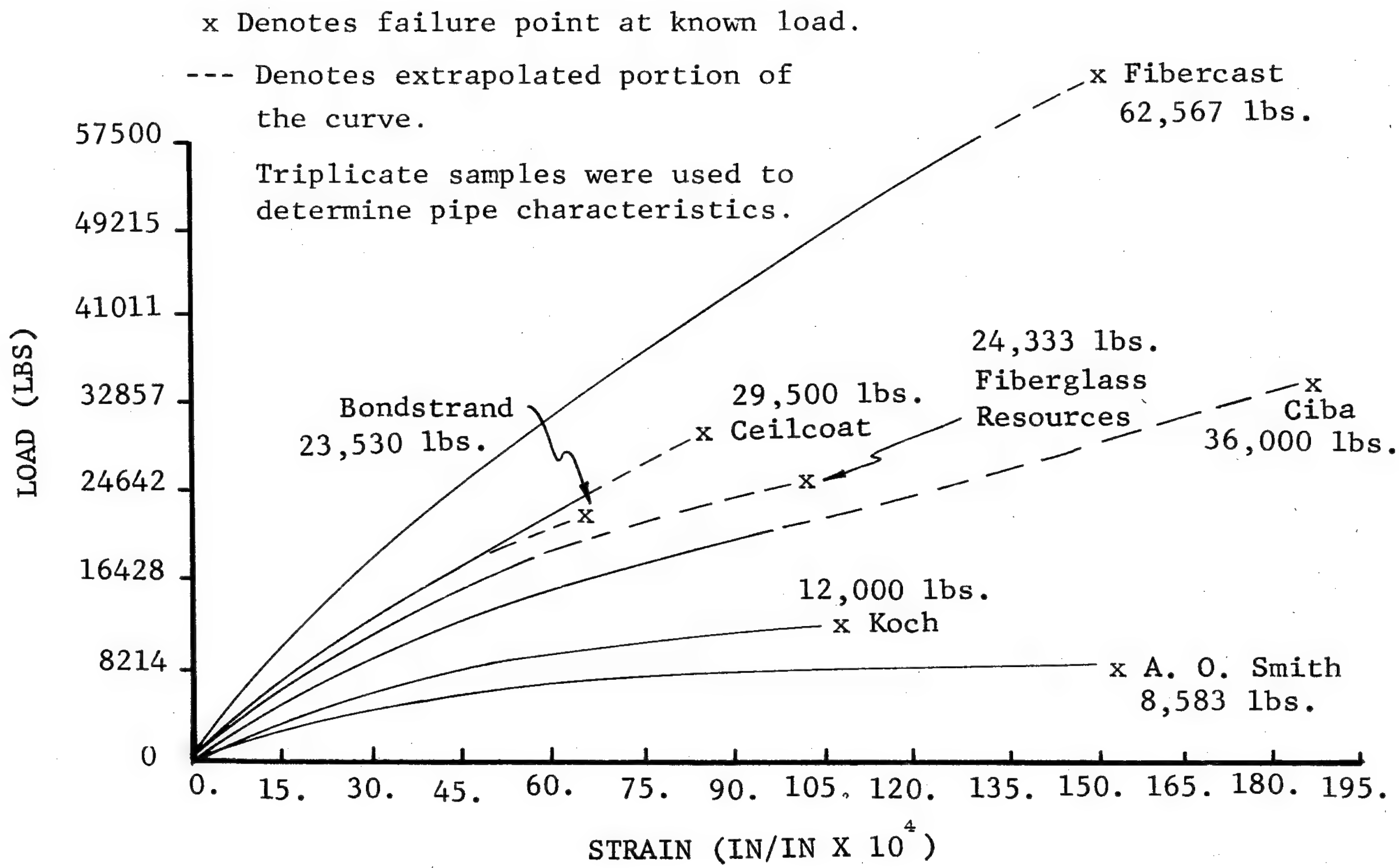



Figure 23. Tension Test 4-inch Specimens

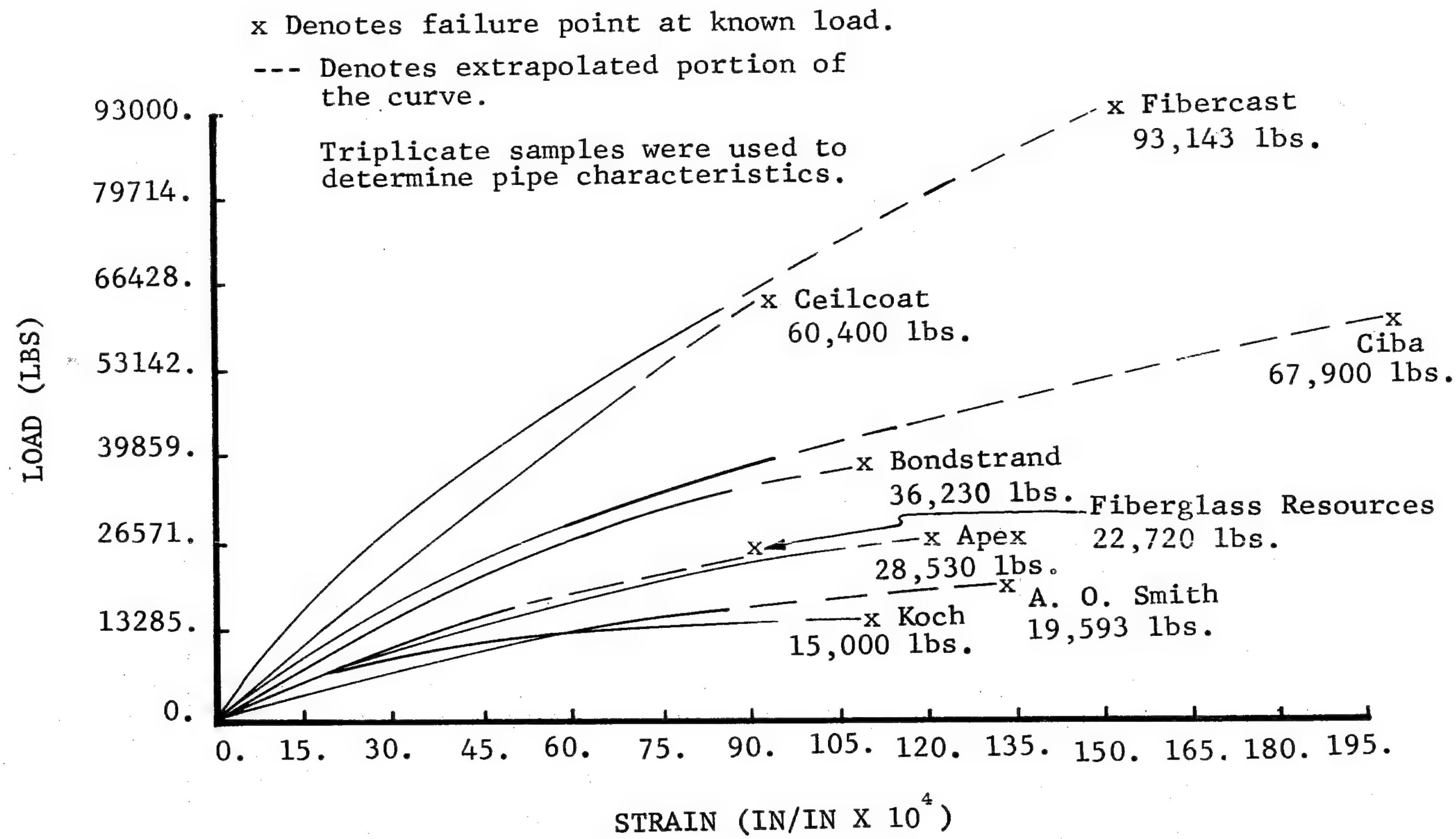



Figure 24. Tension Test 6-inch Specimens

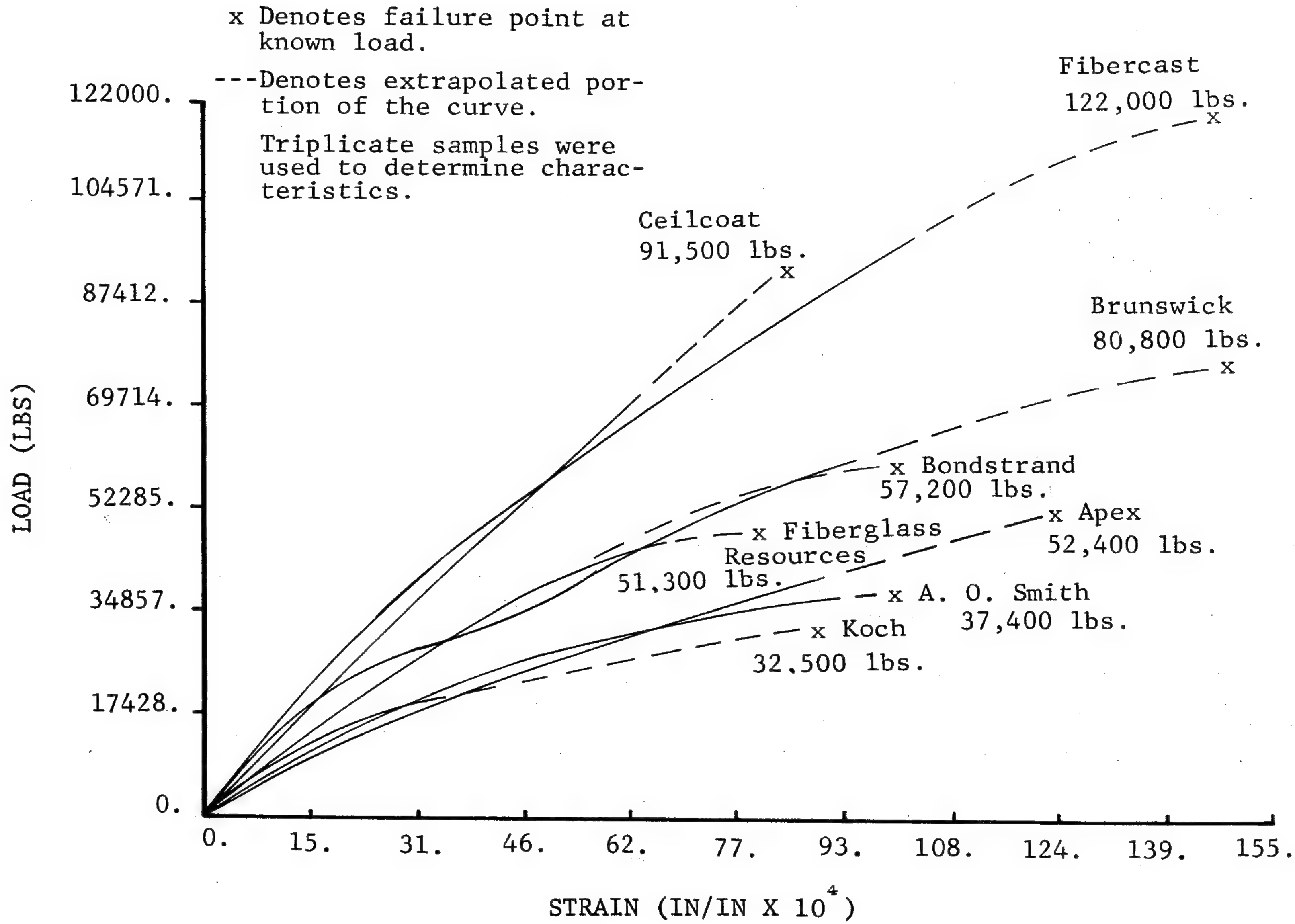



Figure 25. Tension Test 8-inch Specimens

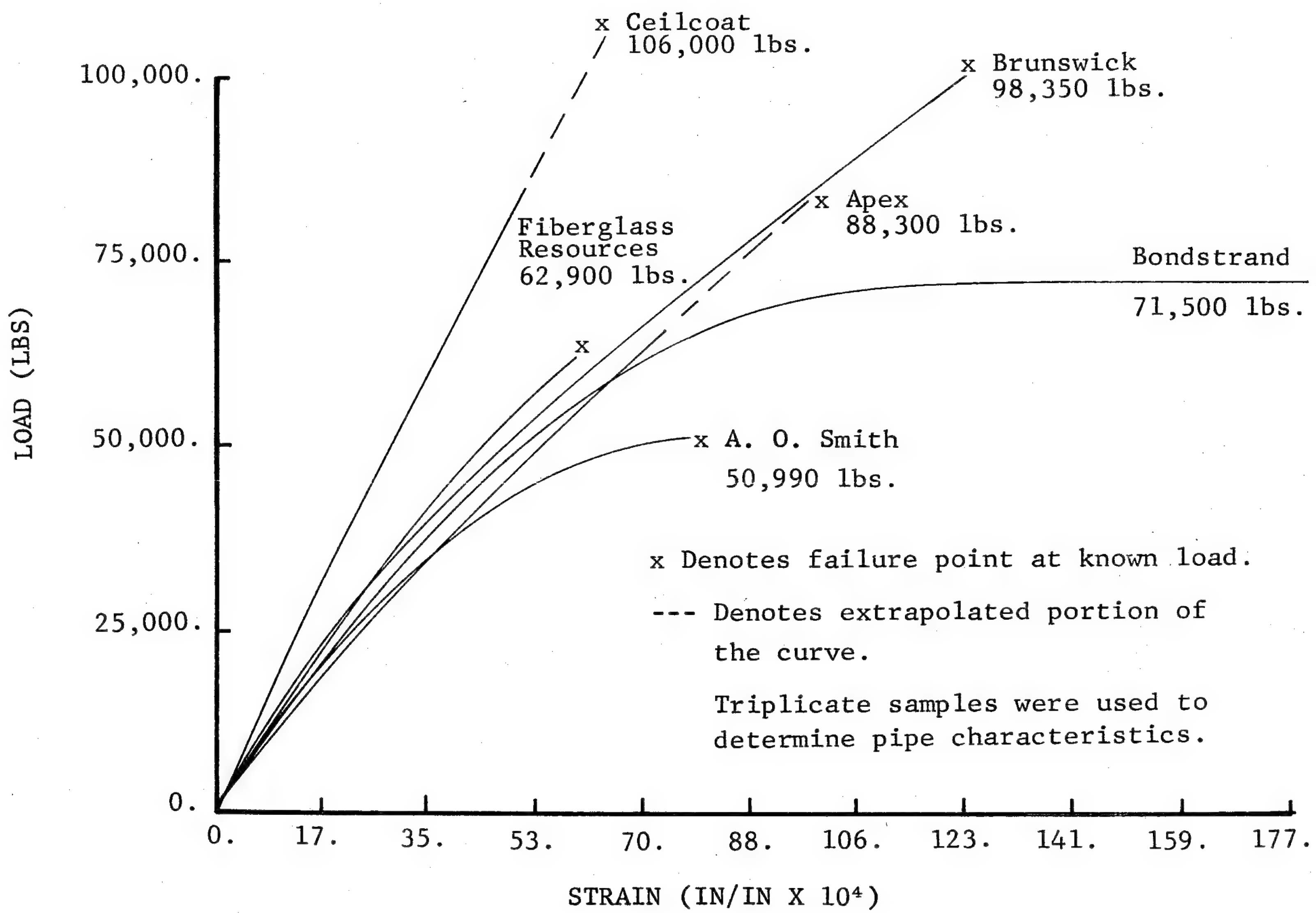



Figure 26. Tension Test 10-inch Specimens

Values for the modulus of elasticity have been calculated by Radian and compared with the manufacturers' data in Table IV.

From the projected curves shown in plots 14 through 26, it can be seen that the ultimate load is less than the product of the modulus of elasticity and the strain. Also, the specimens tested show no yield point as is common in steel.

The values obtained for the tensile modulus of elasticity were calculated by using the secant formula at one-fourth the ultimate load value. After comparing the results of the tension tests, it was felt that this formula would be a fair method to use to compute the modulus values. The initial tangent method recommended by ASTM D2105 is subject to error in cases where a constantly changing slope is present. A larger value for the modulus of elasticity would mean that the material will deform smaller amounts under the same load when compared to a material with a smaller modulus.

As can be seen, there are discrepancies between the manufacturer's reported value of Young's modulus and the value calculated by Radian. Some of the discrepancy between Radian and the manufacturers is caused by the measured dimensional values used in the calculations. Additional discrepancies in the computed values may be due to the fact that some companies compute the modulus for one particular size of pipe and then extrapolate this value to the rest of their products. In the case of a homogeneous material, this is a valid assumption, however, in the case of a nonhomogeneous material like fiber reinforced pipe, this assumption may not be valid. Production techniques are such that a variation in the percentage of fiber content may occur from batch to batch. A small change in the relative amounts of material could effect the modulus computation. In addition the larger pipe sizes do not behave as an exactly scaled up model

TABLE IV

PIPE MODULI OF ELASTICITY COMPUTED BY RADIAN*

| Pipe | Size (in.) | Average Modulus of Elasticity for Each Size | Average Modulus of Elasticity for Each Brand | Manufacturer's Modulus of Elasticity |
|---|---|---|---|---|
| A. O. Smith | 4 | 1.21 | | |
| | 6 | 0.915 | | |
| | 8 | 2.00 | | |
| | 10 | 2.33 | 1.61 | 1.15 |
| Apex | 6 | 0.730 | | |
| | 8 | 0.757 | | |
| | 10 | 0.883 | 0.790 | |
| Bondstrand | 4 | 1.75 | | |
| | 6 | 1.41 | | |
| | 8 | 1.43 | | |
| | 10 | 1.73 | 1.58 | 2.3 |
| Brunswick | 8 | 2.21 | | |
| | 10 | 2.72 | 2.46 | 2.2 |
| Ceilcoat | 4 | 1.16 (Based on Total Area) | | |
| | 6 | 1.44 | | |
| | 8 | 1.27 | | |
| | 10 | 1.46 | 1.33 | 2.5-4.0 |
| Ciba | 4 | 2.50 | 2.62 | 4.0 |
| | 6 | 2.74 | | |
| Fibercast | 4 | 2.25 | | |
| | 6 | 2.14 | | |
| | 8 | 2.17 | 2.18 | 1.5 |
| Fiberglass Resources | 4 | 1.80 | | |
| | 6 | 1.40 | | |
| | 8 | 1.44 | | |
| | 10 | 1.73 | 1.59 | 1.35 |
| Koch | 4 | 1.89 | | |
| | 6 | 1.98 | | |
| | 8 | 1.76 | 1.88 | 1.5 |

* All moduli listed in psi x $10^{-6}$ and based on structural fiber area only.

of the smaller specimens. These factors will both tend to disperse the values obtained for the modulus so that it may not be possible to have a single value pertain to all product sizes.

2. Connections

There were several different types of connections tested including: glued bell and spigot, standard glued coupling, standard threaded coupling, keyed bell and spigot, and keyed standard coupling. In all cases the criteria used to determine the success of the connection in axial tension was whether or not the connection broke before the pipe failed. Because the integrity of the connection may vary according to construction technique used at the well site, the connection should be over designed so that it is as strong as the pipe, even under reasonably poor construction conditions. The test results vary both by type of connection and by manufacturer. For this reason the test results will be presented individually.

(a) Amercoat (Bondstrand Series 2000)

Four-inch standard glued coupling -- failed immediately after the pipe failed in all tests.

Six-inch, 8-inch, 10-inch glued standard coupling -- the glue that bonds the coupling to pipe failed first in all tests.

(b) A. O. Smith (Red Thread)

Four-inch, 6-inch, 8-inch, 10-inch glued bell spigot -- pipe failed first in all tests.

Four-inch, 8-inch, 10-inch glued standard coupling -- pipe failed first in all tests.

Six-inch glued standard coupling -- glue bond at the joint failed first in all tests, but at the same ultimate load as occurred in normal pipe failures.

(c) Apex (A-382)

Six-inch, 8-inch, 10-inch glued standard coupling -- in all but one case the glue that bonds the coupling to the pipe failed. The strength of the coupling varied considerably indicating that the average strength could not be used for design purposes.

(d) Brunswick

Eight-inch keyed bell and spigot -- the joint failed in all tests by shearing the material that formed the outer half of the slot on the bell section (see Figure 27).

Ten-inch keyed bell and spigot -- in all tests the key sheared in half before damage was noted in the pipe or connection.

(e) Ceilcoat (Duracor 1000-9A)

Four-inch standard coupling -- in two cases the pipe failed and in the third case the coupling failed.

Six-inch, 8-inch, 10-inch, the couplings failed (except for one 10-inch specimen where the pipe failed) by the pipe shearing from the coupling surface.

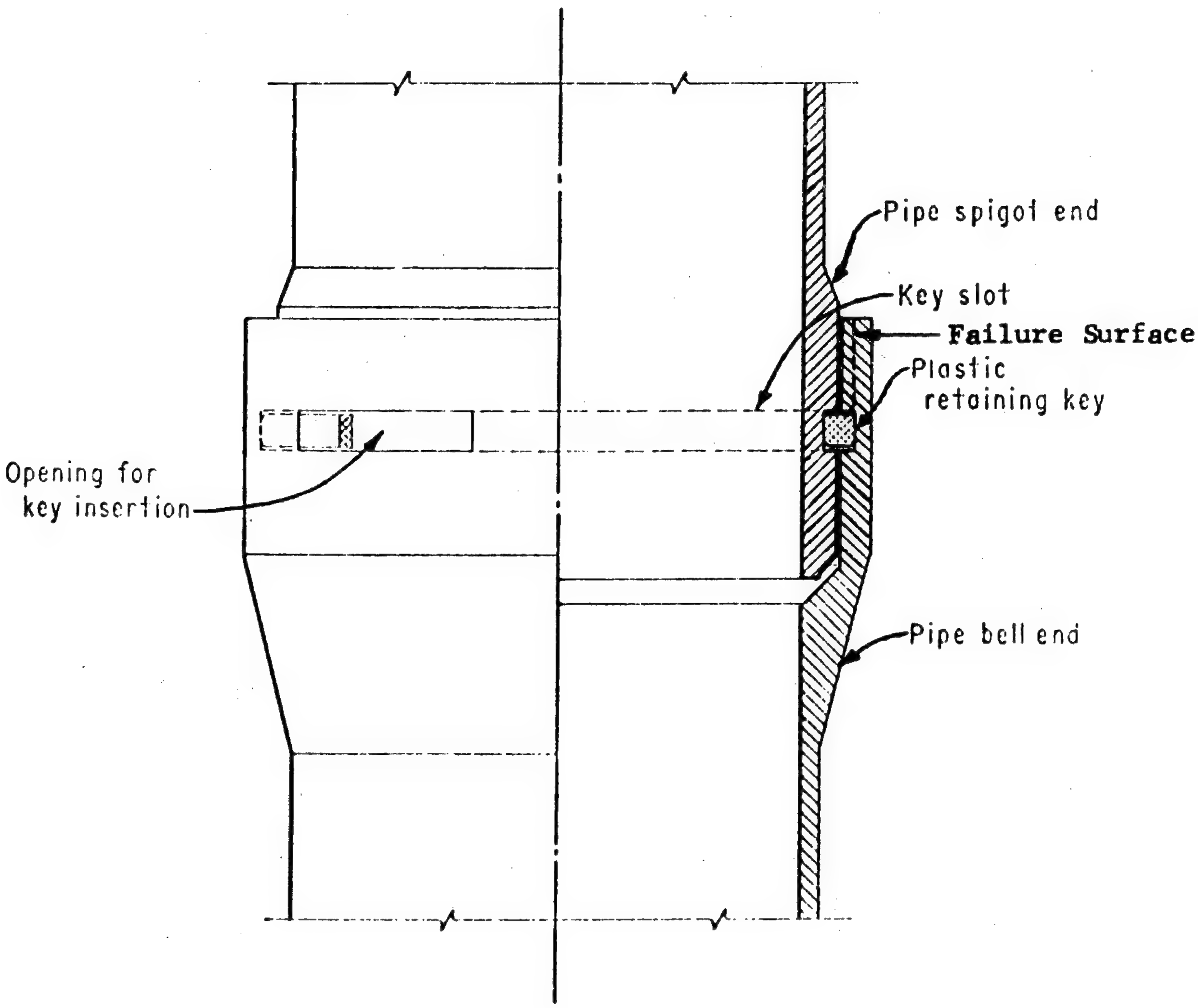



Figure 27. Key Type Coupling
For Fiberglass Tubewell Casing

(f) Ciba (Dualoy 2000)

Four-inch standard glued coupling -- all connections failed by shearing at the glued bond.

Six-inch standard glued coupling -- in all cases but one the coupling failed first.

(g) Fibercast (4-inch GR, 6-inch RB, 8-inch RB)

Four-inch, 6-inch, 8-inch threaded standard coupling -- all connections failed first. In one test the coupling failed at a low load and in the others the threaded surface was sheared.

(h) Fiberglass Resources (KwiKey)

Four-inch keyed standard coupling -- pipe failed before connection.

Six-inch keyed standard coupling -- pipe and coupling failed at the same time.

Eight-inch, 10-inch keyed bell and spigot -- connection failed first by shearing the outer key surface (see Figure 27).

(i) Koch (Blue Streak)

Four-inch, 6-inch, 8-inch standard glued coupling -- in all cases the pipe failed first.

In most cases the connections that did not behave satisfactorily failed in a glued component. A longer contact surface would probably be necessary to improve the strength characteristics of these glued components. The performance of the connections, as compared to the ultimate strength of the pipe, is shown on Table V and in the bar graphs, Figures 28 through 31. As can be seen, most of the couplings broke at loads significantly lower than the ultimate tensile strength of the pipe. There are several things that must be considered in this comparison. One of the most important considerations is the necessity to have a margin of safety that applies to the entire system. This would mean that the maximum available working load would depend on the weakest member. For example, if the pipe and the connection can withstand the same ultimate load, then using a safety factor of four, the working load would be one-fourth the ultimate load of the pipe. If, however, the connection is the weaker member, then the working load would be one-fourth of the ultimate strength of the connection. If the particular pipe and connection being considered are not compatible in the sense that their ultimate strengths are not similar, then higher possible working loads are compromised by the weaker component.

Photographs showing the various types of failures discussed above are shown in Figures 32 through 35.

B. Parallel Plate Compression Test

In this test the specimens were subjected to a deflection perpendicular to the pipe axis. In all cases but the Ceilcoat and Apex pipe, the specimens deformed under the necessary loads without fracturing the glass reinforcement (see Figures 2 and 3). The lined pipe had a tendency to crack in the tensile stress region on opposite sides of the internal wall. Circumferential

TABLE V

AVERAGE CONNECTION STRENGTH COMPARED TO PIPE STRENGTH*

| Pipe | 4-inch Pipe | 4-inch Conn. | 6-inch Pipe | 6-inch Conn. | 8-inch Pipe | 8-inch Conn. | 10-inch Pipe | 10-inch Conn. |
|---|---|---|---|---|---|---|---|---|
| A. O. Smith | | | | | | | | |
| Coupling | 8,580 | 8,460 | 19,600 | 19,900 | 37,400 | 36,300 | 51,000 | 53,100 |
| Bell & Spigot | 8,580 | 8,960 | 19,600 | 20,700 | 37,400 | 38,600 | 51,000 | 55,700 |
| Apex | --- | --- | 28,500 | 12,700 | 53,100 | 41,600 | 88,300 | 25,300 |
| Bondstrand | 23,500 | 22,900 | 36,200 | 31,800 | 57,200 | 47,500 | 71,500 | 52,200 |
| Brunswick | --- | --- | --- | --- | 80,800 | 45,800 | 98,400 | 64,700 |
| Ceilcoat | 29,500 | 27,300 | 60,100 | 41,900 | 91,500 | 63,600 | 106,000 | 81,600 |
| Ciba | 36,000 | 39,000 | 67,900 | 46,300 | --- | --- | --- | --- |
| Fibercast | 62,600 | 47,400 | 93,100 | 68,800 | 121,500 | 86,300 | --- | --- |
| Fiberglass Resources | 24,300 | 26,100 | 22,700 | 21,500 | 51,300 | 38,900 | 62,900 | 36,000 |
| Koch | 12,000 | 12,300 | 15,000 | 15,500 | 32,500 | 32,700 | --- | --- |

* All strengths listed in pounds.

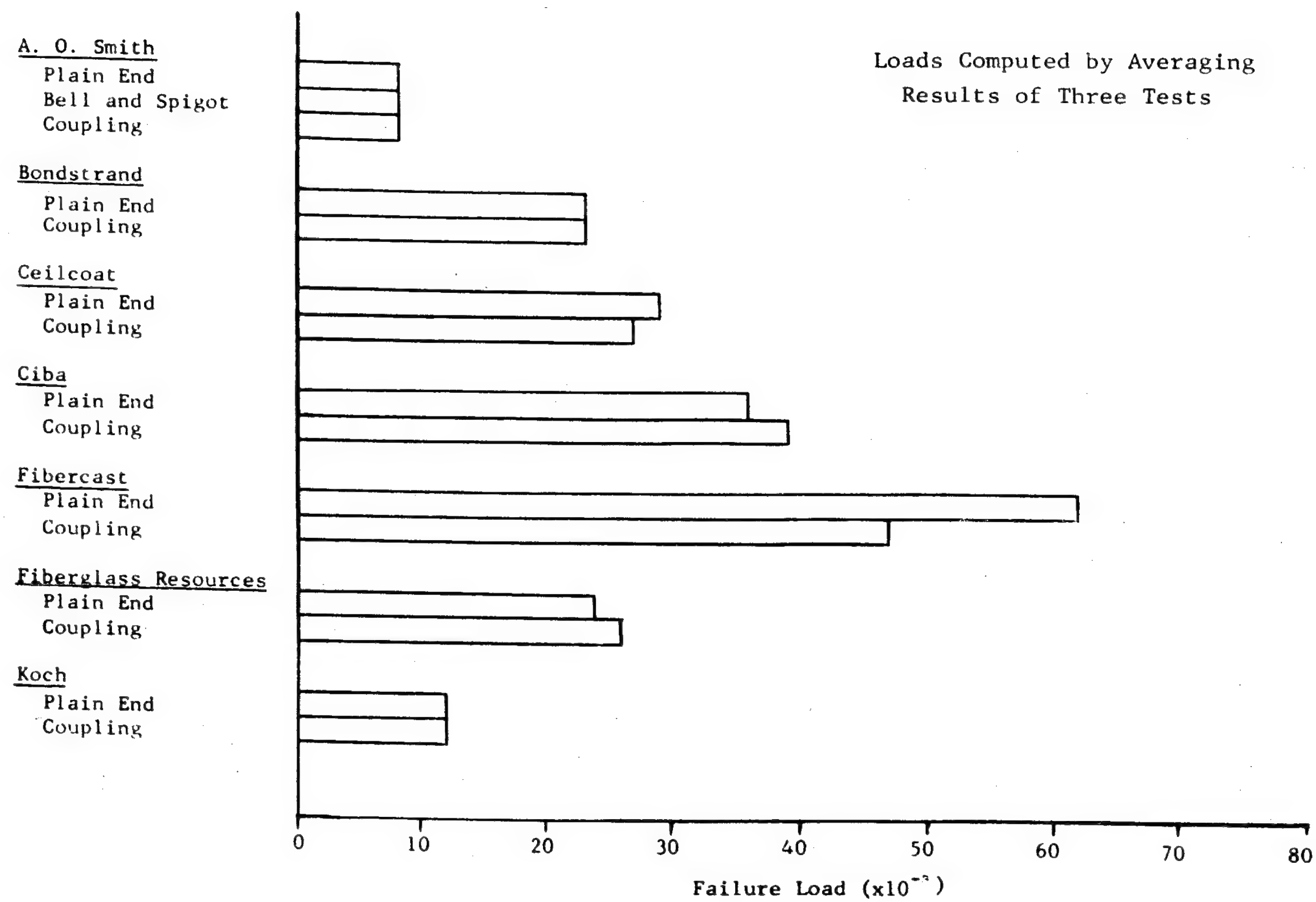



Figure 28. Results Of Tension Test On 4-inch Connections As Compared To Pipe Strength

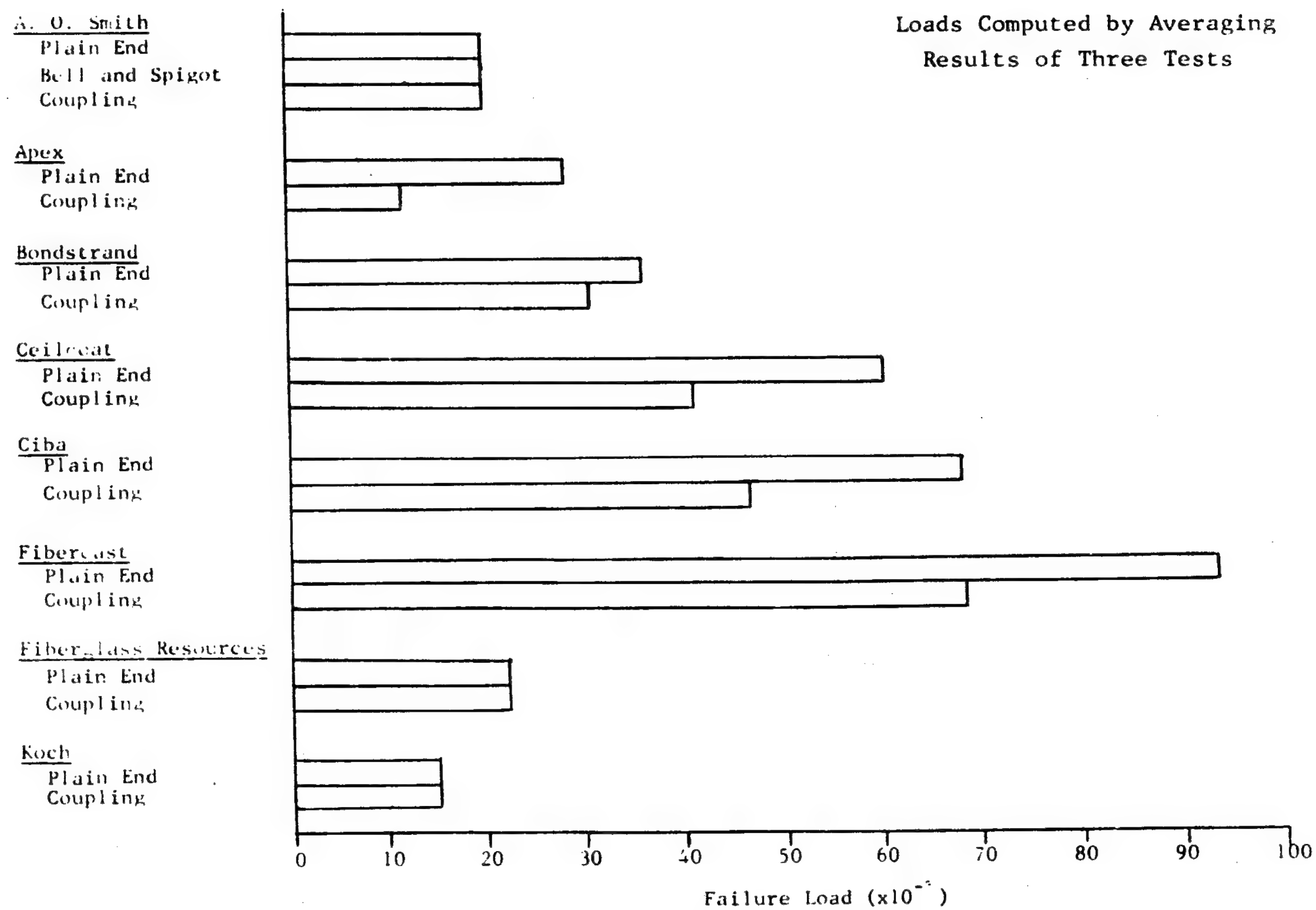



Figure 29. Results Of Tension Test On 6-inch Connections As Compared To Pipe Strength

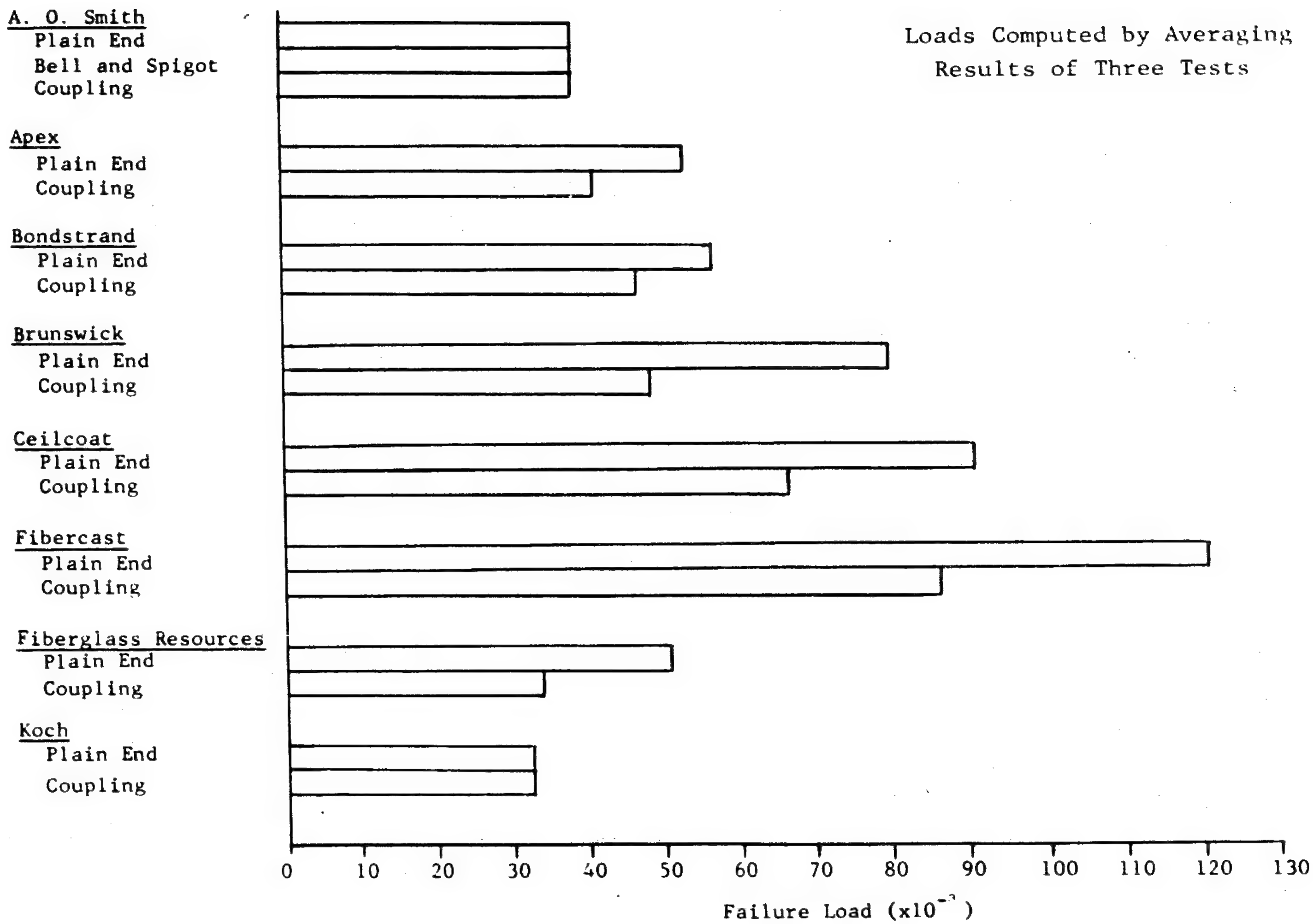



Figure 30. Results Of Tension Test On 8-inch Connections As Compared To Pipe Strength

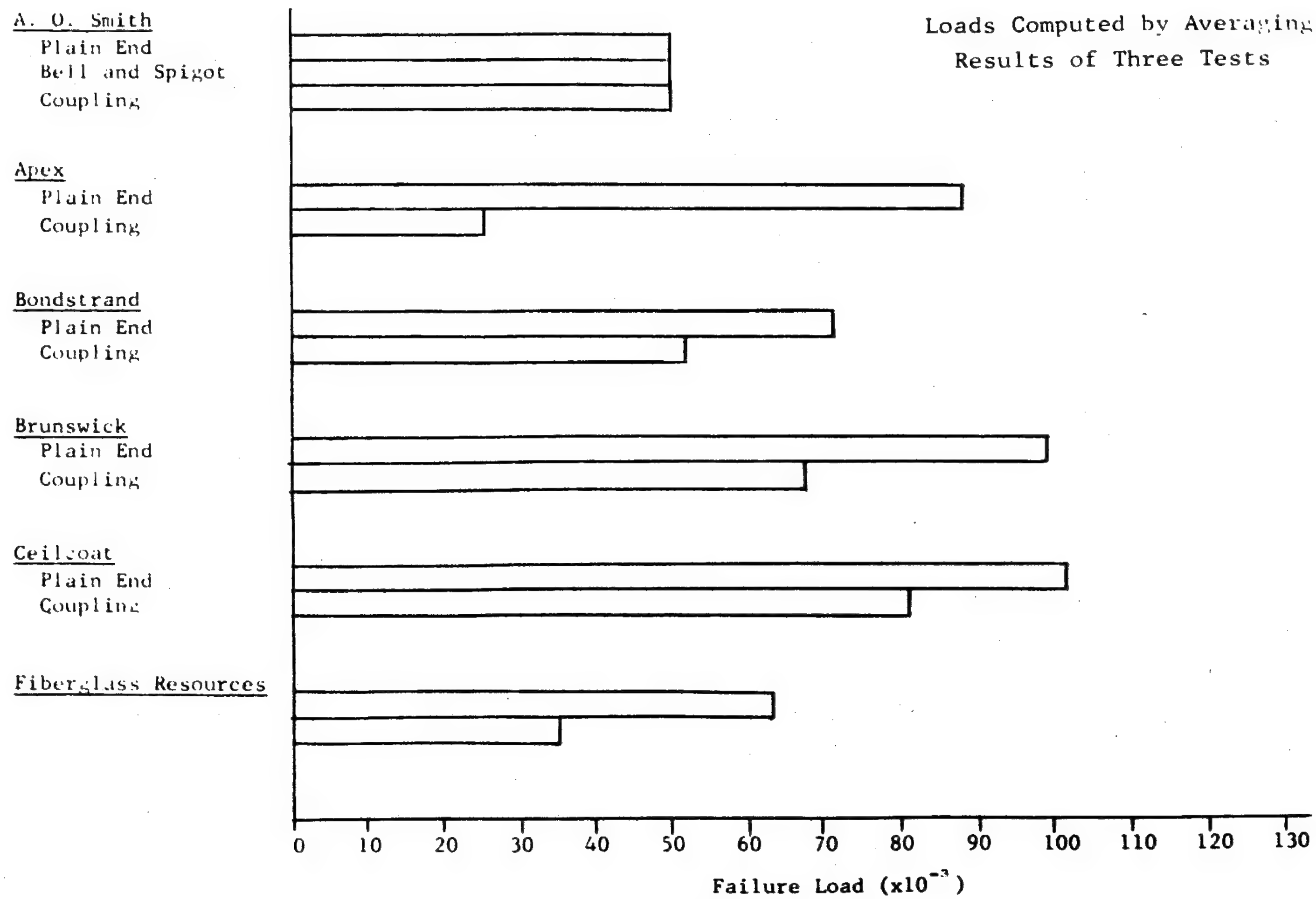



Figure 31. Results Of Tension Test On 10-inch Connections As Compared To Pipe Strength

Figure 32. Example Of A Successful Coupling

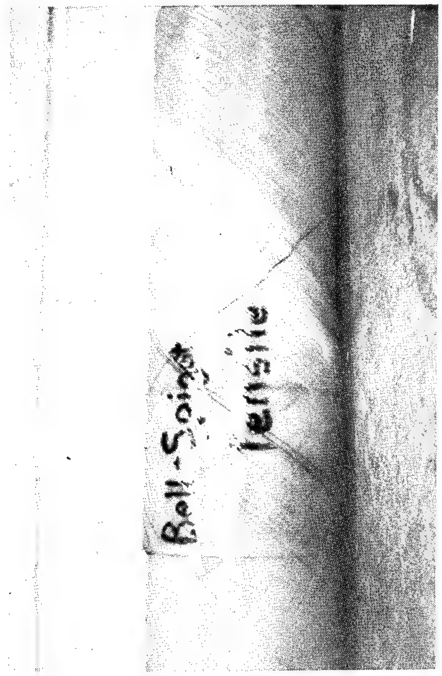



Figure 33. Example Of A Successful Bell And Spigot

Figure 34. Failure Of Threaded Coupling

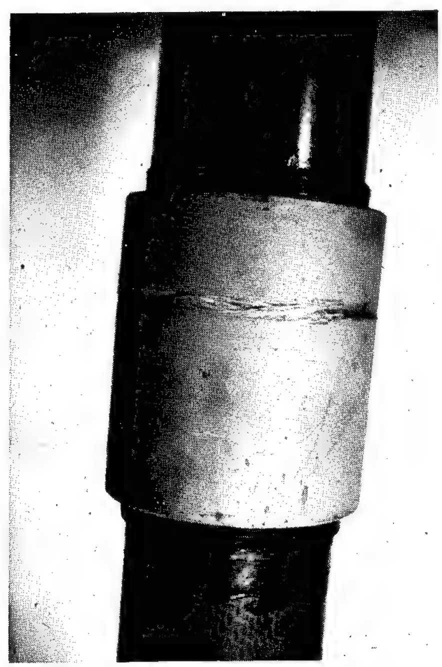


Figure 35. Coupling Failure

Circumferential cracks extended around most lined specimens indicating a possible loss of liner protection. When the specimens were unloaded, the pipe returned to approximately the initial shape indicating that the specimens behaved relatively elastically under the load conditions (see Figures 36 and 37). The generally straight path of these curves is typical of an elastic deformation.

Table VI presents the ultimate load and the ultimate deflection for this test. The ultimate load is defined as the greatest load supported for a deflection up to 30% of the pipe diameter.

The Brunswick samples behaved well in this test because the fiber reinforcement perpendicular to the pipe axis adds considerable strength for resisting compressive loads of this type. It is possible that this glass matrix forms an arch type support because the fibers are oriented to absorb the entire tensile stress. The longitudinal fibers do not contribute to the pipe performance under the loading design used in this test. An explanation of this type is feasible because an examination of the fiber thicknesses on Table I, page 40, shows that Brunswick has a relatively small amount of glass reinforcement. Although the strength of the other filament wound products increases with increased fiber thickness, it is significant that the different fiber orientation of the Brunswick specimens is the primary contributor to its increased strength.

Fibercast and Koch did not submit a 10-inch pipe, so a comparison is only available in the 8-inch pipe. The 8-inch Fibercast specimens did exhibit a different effect than the filament wound sample. The glass mat used in the centrifugal casting process does not seem to support a load of this type as well as the filament would pipe. The liner on the Fibercast specimens was damaged more than in some other cases, possibly because of

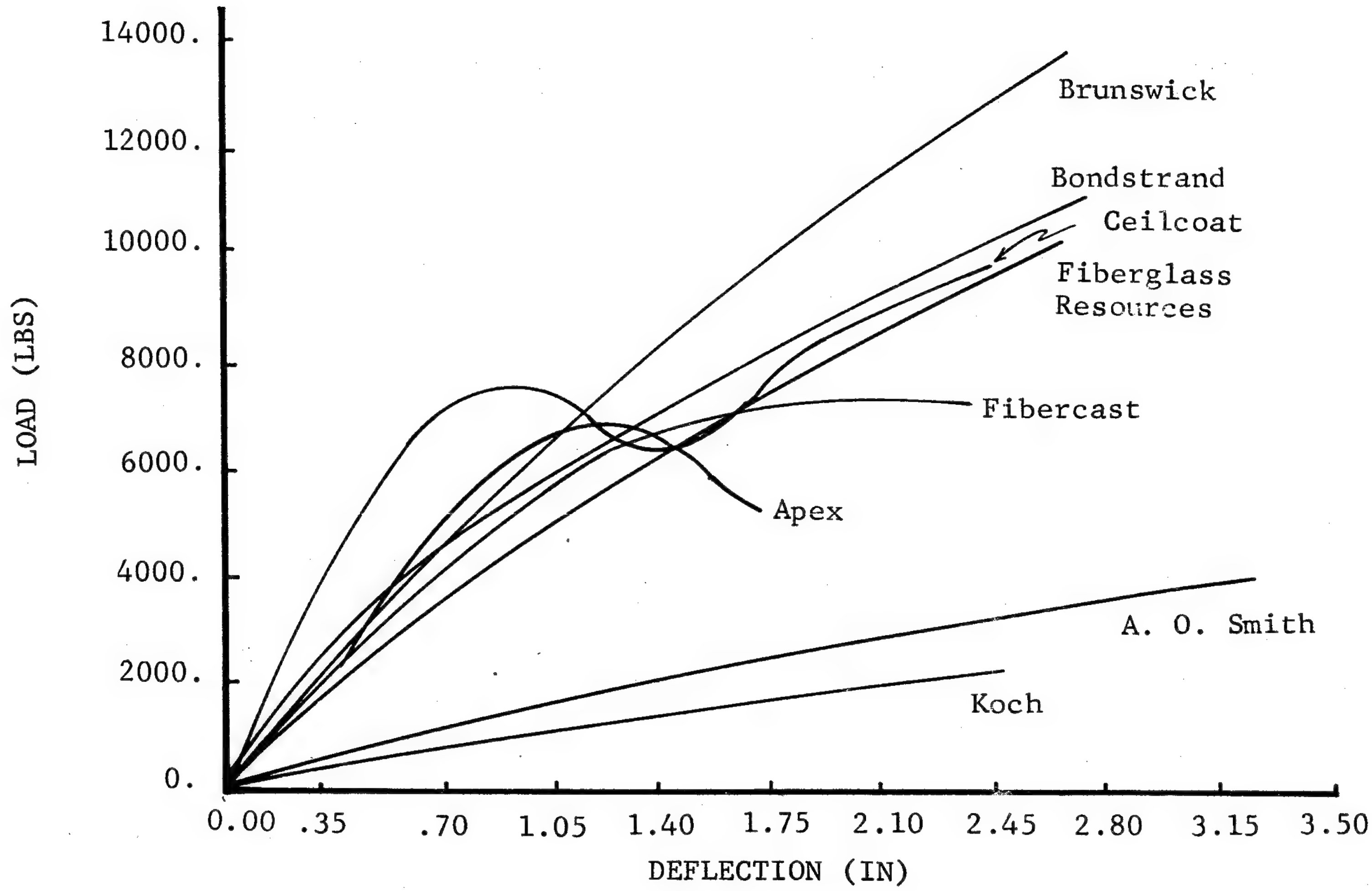



Figure 36. Parallel Plate Test 8-inch Specimens

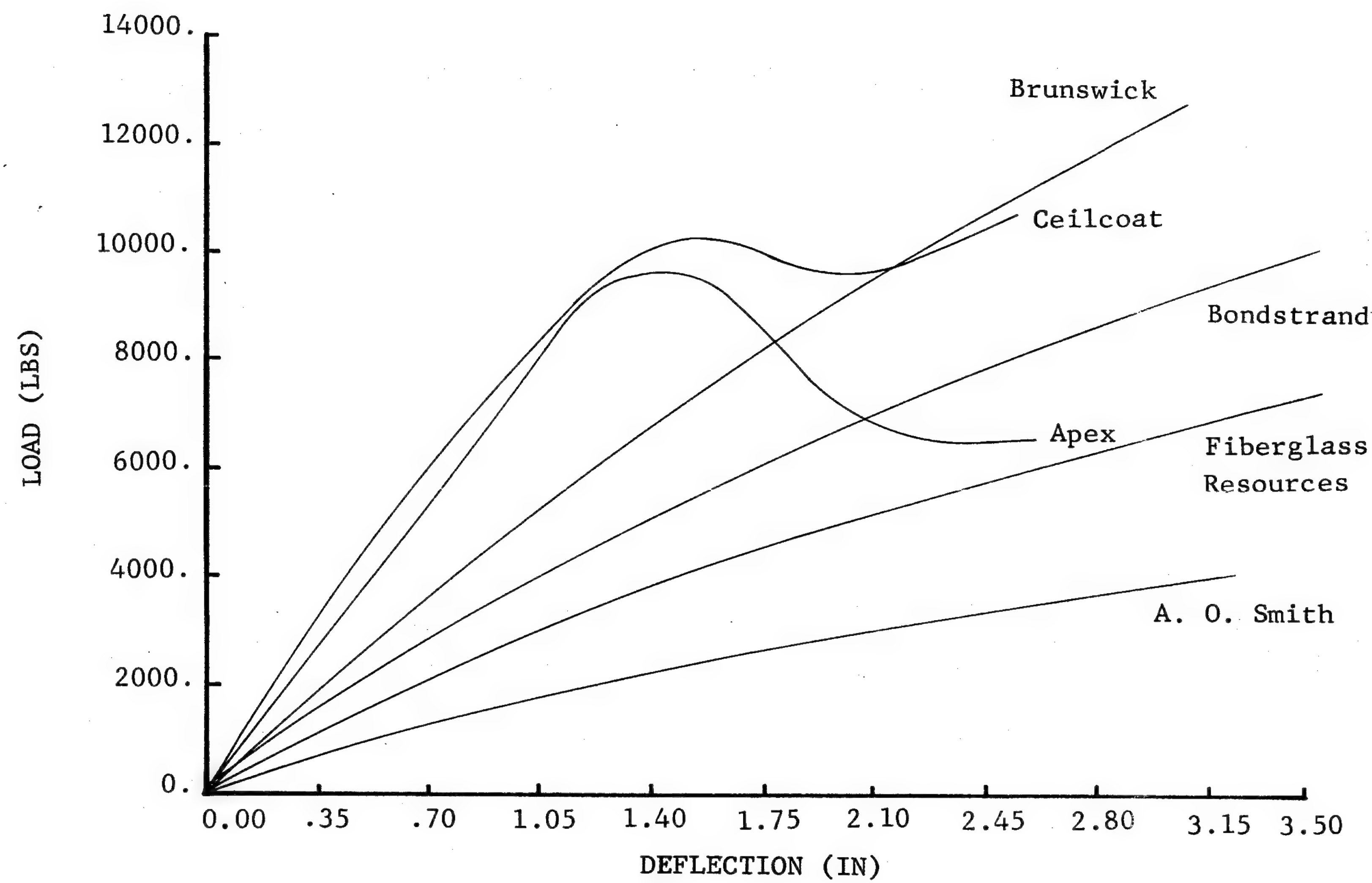



Figure 37. Parallel Plate Test 10-inch Specimens

## TABLE VI

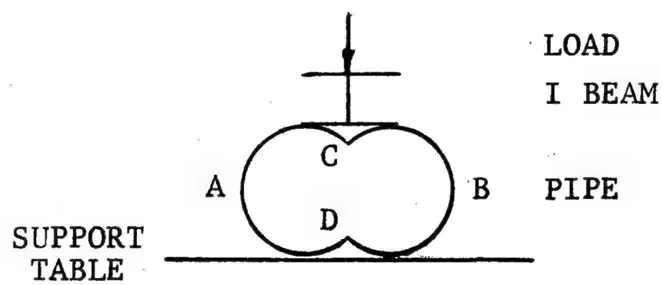
## RESULTS FOR THE PARALLEL PLATE TEST

| Pipe | 8-inch Ultimate Load* (lbs.) | 8-inch Ultimate Deflection (in.) | 10-inch Ultimate Load* (lbs.) | 10-inch Ultimate Deflection (in) |
|---|---|---|---|---|
| A. O. Smith | 3,100 | 2.4 | 3,900 | 3.0 |
| Apex | 6,900 | 1.2 | 9,200 | 1.5 |
| Bondstrand | 10,000 | 2.4 | 8,900 | 3.0 |
| Brunswick | 13,000 | 2.4 | 13,000 | 3.0 |
| Ceilcoat | 8,400 | 0.87 | 11,000 | 1.4 |
| Fibercast | 7,700 | 1.6 | --- | --- |
| Fiberglass Resources | 9,500 | 2.4 | 6,700 | 3.0 |
| Koch | 2,400 | 2.4 | --- | --- |

*The ultimate load is defined as the greatest load supported by the pipe for a deflection for the 8- and 10-inch pipe of up to 2.4 and 3.0 inches, respectively.

its thickness. This particular liner behaved in a more brittle fashion than the other liners opening the possibility that the rest of the epoxy used in the pipe behaved in the same manner. If this is what happened, the Fibercast specimen displayed a unique curve because of the inability of the epoxy to deform without losing its load carrying capability due to brittle behavior.

The Apex and Ceilcoat specimens exhibited an unusual behavior in the range of deflection by supporting a peak load and then drastically reducing the supported load with continued deflection. Both pipes are brittle and fracture at the peak. Many of the fibers in the Ceilcoat pipe fractured and many of the chopped fibers in the Apex pipe separated. As the Ceilcoat pipe continues to be deflected, it supports a load higher than the peak value. At this point the pipe maintains a shape as shown below:




This diagram shows that the pipe has partially collapsed, but in order to totally collapse, the sides at A and B must fracture. It should be noted that the distanct $\overline{CD}$ is less than the diameter of a column pipe. Therefore, this increased supported load would be of no advantage because of the possible rupture of the column pipe. The Apex pipe also went through a similar peak load, but at this point it collapsed so that it supported only a reduced load.

These results can be used to arrive at general conclusions about the ability of the product to absorb a uniform load along

the pipe axis. It would be most desirable to have a pipe that is capable of maintaining its original shape under uniform loading without damage to the material. These criteria seem to be best fulfilled by the Brunswick samples.

C. Tup Puncture Test

The results from the tup test did not necessarily vary according to the type of manufacturing process. For example, the centrifugally cast Fibercast pipe behaved similarly to the filament wound pipe. The important parameters for determining the relative behavior of the specimens are fiber layer thickness, flexibility of pipe, and the winding angles of the glass fibers. In general, the two basic principles involved are: the greater the thickness of the fiber layer, the stronger the pipe; and, the more flexible the pipe, the less likely is the tup to pierce the wall thereby ultimately withstanding a high load (see Table VII).

A comparison of the 8- and 10-inch specimens by manufacturer (Figures 38 and 39) shows that when there is a significant difference in fiber layer thickness, the specimens with the larger thickness are the strongest. It can be concluded that when more fibers are added to the pipe wall, a higher load can be obtained without raising the stress level in the individual fibers. In the Brunswick specimens both sizes have approximately the same fiber layer thickness. In this case, a factor in determining the higher ultimate load experienced by the 8-inch specimens, is the unique orientation of the Brunswick fibers. Since the fibers in these samples run parallel and perpendicular to the axis, failure occurs when the tup head either shears the glass fibers oriented parallel to the axis or separates the fibers perpendicular to the axis. The 8-inch

## TABLE VII

## RESULTS FOR THE TUP TEST

| Pipe | 8-inch Ultimate Load (lbs.) | 8-inch Ultimate Deflection (in.) | 10-inch Ultimate Load (lbs.) | 10-inch Ultimate Deflection (in.) |
|---|---|---|---|---|
| A. O. Smith | 1,500 | 1.4 | 2,000 | 2.2 |
| Apex | 1,300 | 0.39 | 1,600 | 0.48 |
| Bondstrand | 1,800 | 0.82 | 1,900 | 1.1 |
| Brunswick | 1,300 | 0.45 | 1,100 | 0.41 |
| Ceilcoat | 2,200 | 0.35 | 2,600 | 0.51 |
| Fibercast | 2,000 | 0.79 | --- | --- |
| Fiberglass Resources | 2,000 | 0.75 | 1,900 | 0.88 |
| Koch | 1,300 | 1.4 | --- | --- |

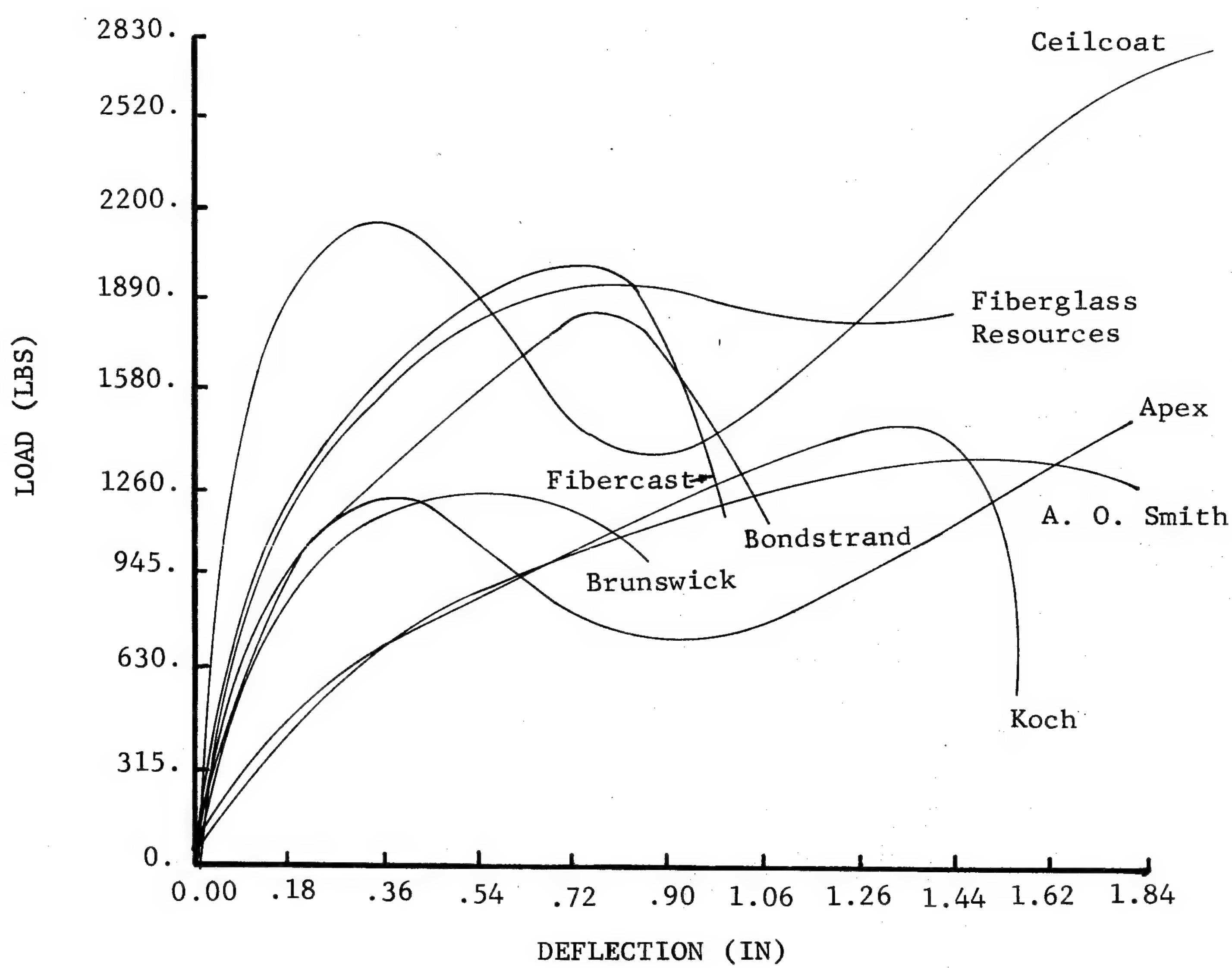



Figure 38. Tup Test 8-inch Specimens

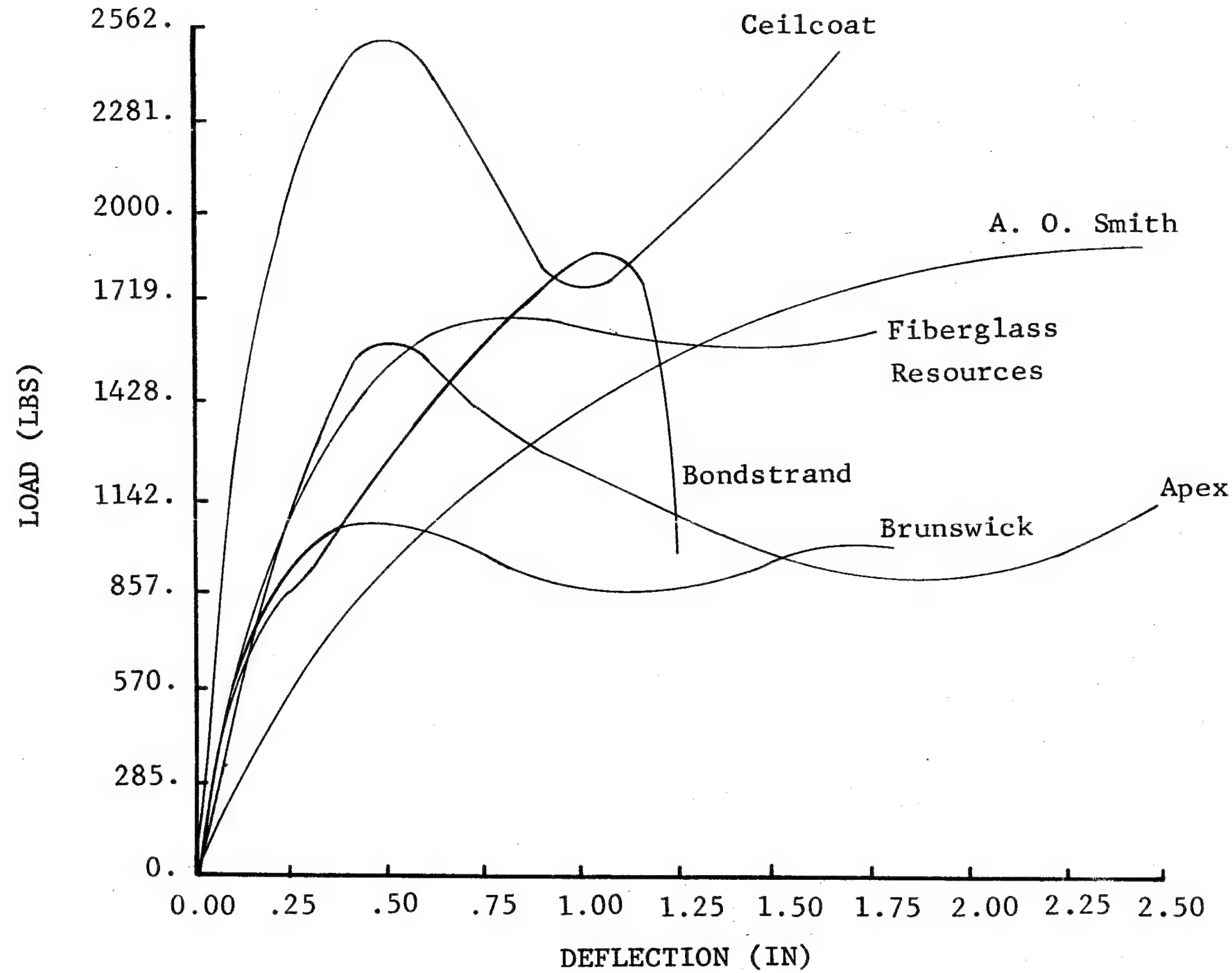



Figure 39. Tup Test 10-inch Specimens

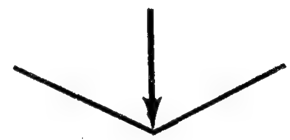
pipe supports more load because, due to its smaller diameter, it maintains an "arch" shape, whereas the 10-inch pipe flattens. The arch configuration naturally lends itself to supporting a higher relative load than does the flat surface. The difference in the shapes of the two Brunswick curves is caused by the additional deflection used in the test of the 10-inch specimens. It is possible that the 8-inch specimens would have behaved in the same general manner if a larger deflection had been utilized.

In both the Apex and Ceilcoat specimens, due to the thick walls and brittle behavior, little deflection occurred for relatively large loads. The tup finally fractured the wall at a low deflection. As the tup progressed through the wall, the pipe supported greater loads. This was probably due because the tup head increases in diameter the further it presses into the pipe wall. In this way the load can be distributed over a larger area thereby reducing the stress. This behavior might be beneficial for water well casing since the same load can be supported at lower deflections relative to the other brands tested.

In comparing the specimens by size, the same general trends apply with the exception of the Brunswick specimens. The ultimate loads increase as the fiber thicknesses increase. This effect is demonstrated in Table VII. However, there are some other noticeable features. The Fibercast 8-inch specimens, Apex 8- and 10-inch, Ceilcoat 8- and 10-inch, Bondstrand 8- and 10-inch specimens fail abruptly. The A. O. Smith 8- and 10-inch specimens and the Fiberglass Resources 8- and 10-inch specimens withstand a continuously increasing load or maintain their maximum loads over a large deflection. These characteristics are due to the flexibility of the pipe. An example of how increased flexibility can strengthen resistance to a point load is shown by the fact that if a vertical load is applied to a

horizontal fiber, a larger stress is exerted on the fiber than if the fiber is allowed to deflect under that same load.

Higher Stress
Case A



Lower Stress
Case B

When the pipe reacts similarly to Case A, the fibers break suddenly and release most of the load as is shown in Figures 38 and 39. As seen in Figure 6 the flexible pipe somewhat aligns its fibers with the applied load. In both the 8- and 10-inch specimens from A. O. Smith, the flexibility allows the pipe to support a proportionally higher load in comparison with the fiber thicknesses. However, even though the A. O. Smith specimens can ultimately resist a high tup load, at the same loads it experiences a greater deflection than some other brands. The large deflection could interfere with the column pipe in a water well. The properties displayed by the Fiberglass Resources casing might be advantageous because it has a small relative deflection for a given load and it maintains its maximum load over a large deflection.

### D. Hydrostatic Collapse Test

In this test, specimens of well screen were subjected to a biaxial external pressure. The screen is normally subjected to pressures of this type when used as a section of the casing in water wells.

The hydrostatic collapse pressure of a homogeneous, tubular material due to external pressure can be represented by:

$$P = K(T/D)^3 \qquad \text{(Breese Equation)}$$

where $P$ = ultimate collapse pressure

$K = 2E/1-\mu^2$

$T$ = wall thickness

$D$ = diameter

$\mu$ = Poisson's ratio

A relationship of this general form should pertain to the nonhomogeneous fiberglass reinforced screen tested by Radian. From this equation it is obvious that the pressure increases exponentially as the wall thickness increases linearly and the pressure decreases exponentially as the diameter increases linearly. Because the diameters change much faster than the wall thicknesses when going from one size of pipe to another, it is expected that the larger sizes of pipe would not be as strong as the smaller sizes.

All specimens were tested in the pressure vessel shown in Figure 40.

All of the specimens failed through the path of least material, i.e., a plane running through the slots (see Figure 41).

The results of this test are shown on Table VIII and have been graphed (Figure 42) so that a visual comparison of the various products can be made. The boiled specimens lost about ten percent (10%) of the ultimate strength obtained by the normal samples. The boiling was designed to weaken the screen by allowing hot water to chemically and physically attack the glass-resin bond. This process represents a probable loss in strength after the screen is submerged in a well for a long period of time.

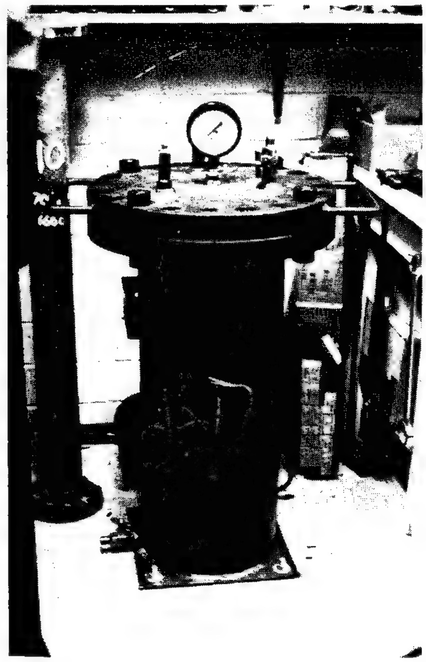


Figure 40. Pressure Vessel Used In Hydrostatic Tests

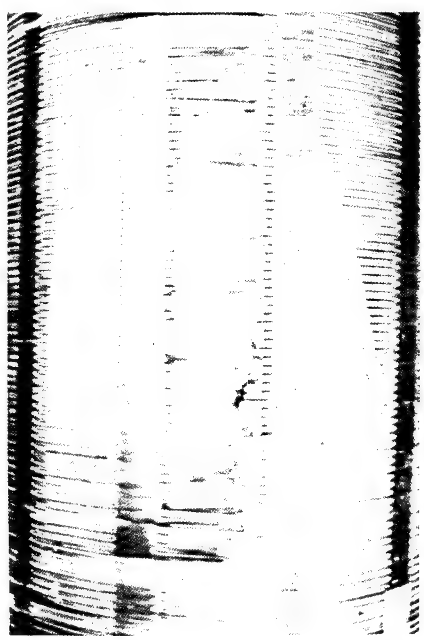


Figure 41. Failure By External Pressure On Screen Specimen

## TABLE VIII

## RESULTS OF HYDROSTATIC COMPRESSION TEST*

| Pipe | 8-inch Normal | 8-inch Boiled | 10-inch Normal | 10-inch Boiled |
|---|---|---|---|---|
| A. O. Smith | 36 | 31 | 30 | 26 |
| Bondstrand | 87 | 78 | 40 | 38 |
| Brunswick | 130 | 120 | 71 | 64 |
| Fiberglass Resources | 154 | 140 | 75 | 70 |
| Rod Base Stainless Steel Screen Type 304 | 230 | --- | 195 | --- |

* All units of listed values in psi.

NOTE: These values represent the average external pressure that causes failure in the specimens tested.

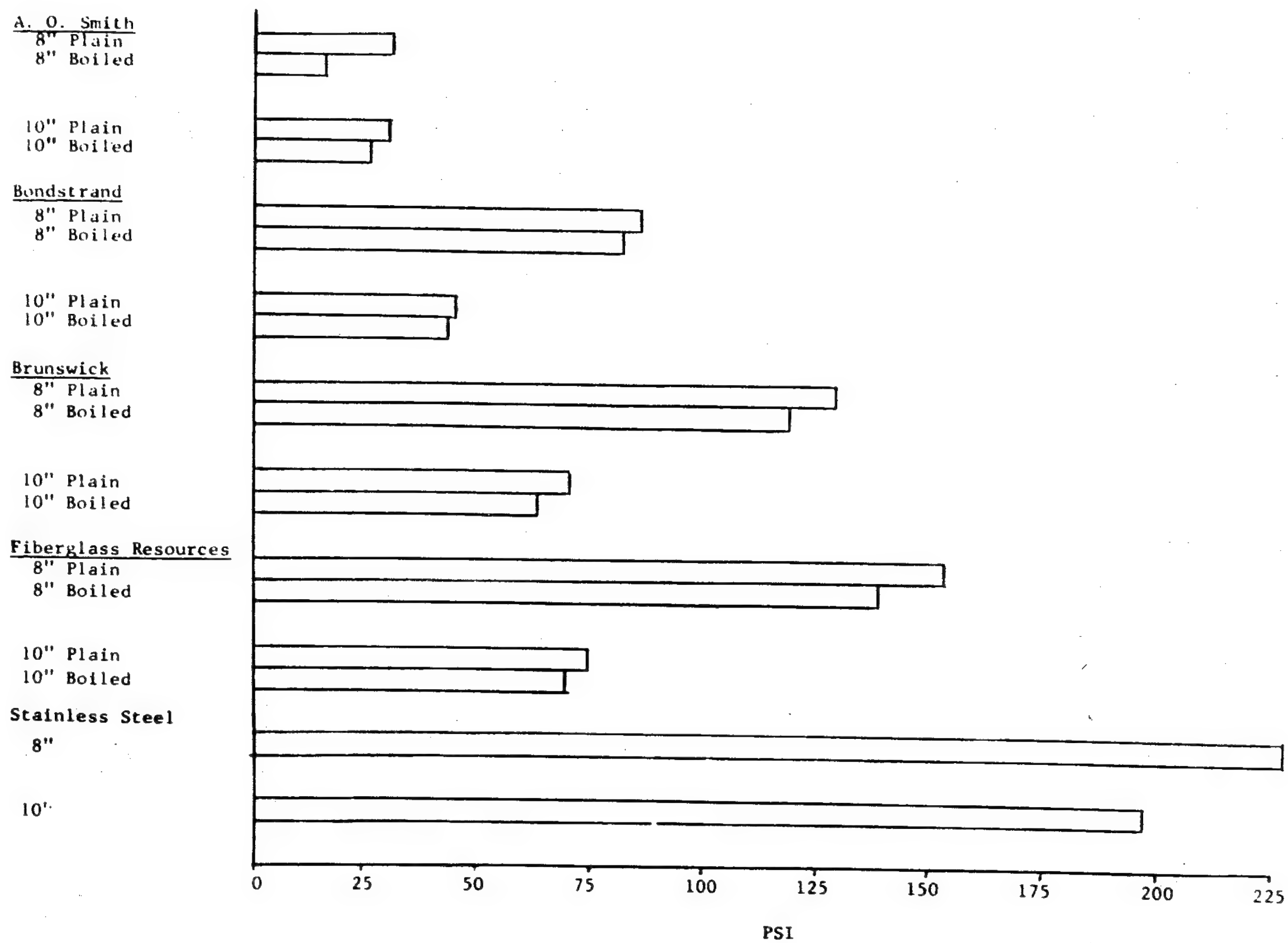



Figure 42. Average Ultimate Pressures Of The Hydrostatic Tests

The A. O. Smith screen had the least drop in pressure comparing the 8- and 10-inch tests; however, the ultimate pressure capabilities of the 8-inch A. O. Smith screen were much lower than the other products. The Brunswick screen behaved well, probably for the same reasons it did well in the parallel plate compression test. The glass fibers perpendicular to the pipe axis are oriented properly to absorb a compression load and the slots are aligned so that the smallest number of glass fibers are cut in the slotting process. In addition it might be noted that this strength was achieved with a smaller measured wall thickness than the next best product. The Amercoat specimens tended to fail suddenly, breaking into numerous pieces, where the other products deformed to relieve the pressure and tended to retain their shape after failure (Figure 41). The Fiberglass Resources screening withstood the greatest pressures. By examining the wall thickness and diameter, according to the Breese Equation the Fiberglass Resources pipe should be stronger than the Brunswick pipe. Another contributing factor is the slotting arrangement of the Fiberglass Resources pipe. Its slots were oriented in a somewhat random row, whereas all other brands had the rows oriented exactly parallel to the pipe axis.

As a result of these tests, it seems reasonable that if the screening produced by the filament wound process was slotted on the same angle as the fiber orientation, fewer reinforcing fibers would be cut and perhaps the ultimate strength of the screen would be increased. Possibly the more random orientation of the Fiberglass Resources slotting helped increase its hydrostatic strength.

For comparison of FRP screen to stainless steel screen, a sample of each 8- and 10-inch rod base screen from the Howard Smith Company of Houston, Texas was crushed. Both the 8- and 10-inch stainless steel screen (type 304) had 0.090-inch wrap wire

and 0.179-inch rib wire. The 8-inch screen had a slot width of 0.20-inch and an open area of 59 square inches per foot. The 10-inch screen had a slot width of 0.60-inch and an open area of approximately 165 square inches per foot. As shown in Figure 42 and Table VIII, the steel screen is somewhat stronger than the FRP screen. However, an important point is that some FRP screen is comparable in this test to the intermediate strength steel screen. The strength value for the steel screen should not be considered as the highest value for commercially available screening. Stronger screens are available using larger and stronger rib and wrap wire.

### E. Creep Test

The results of the creep test give an indication of how a particular column pipe might be expected to perform after a long period of constant use. The pipe is tested at a variety of loads to determine the reliability of the manufacturers' recommended loading under working conditions. The test apparatus is shown in Figure 43.

Most companies determine the ultimate failure load of their product in tension and then use this value to determine a safe working load. To obtain the ultimate tensile strength of their product, they use an internal pressure to burst the pipe and then calculate a hoop stress value. A common practice is to take 20% - 30% of the ultimate stress and use that value to calculate the working load. The creep research performed at Radian Corporation shows that an approach of this type can cause problems that may not be adequately considered in the engineering analysis of long term pipe strength. Although the failure mechanisms are similar, as seen in Figures 44 and 45, neither an axial tensile test of the type conducted by Radian (Test Results,

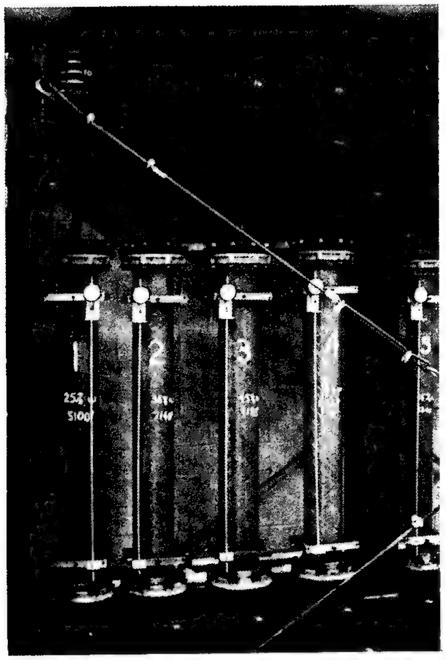


Figure 43. Creep Test Apparatus

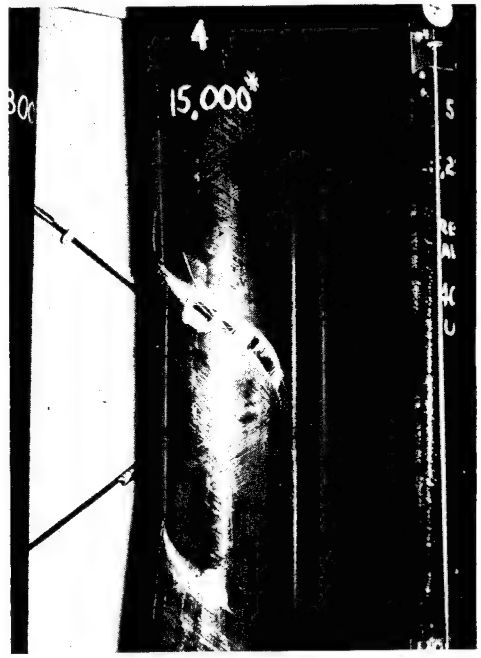



Figure 44. Result Of Failure By Creep

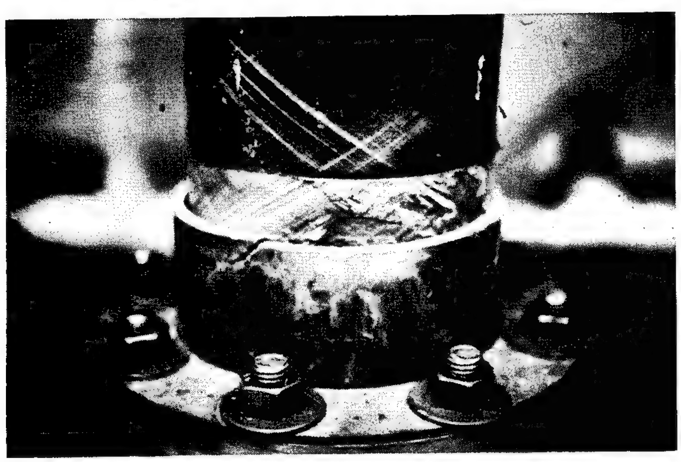


Figure 45. Failure In Specimen Caused Flange Failure

Part A), nor a hydrostatic burst test can reliably indicate the performance of a pipe under long term axial tension load. As can be seen in Table IX with all other parameters held constant, varying the load had a significant effect on the creep rate.

All of the specimens tested had a large initial deformation caused by stress relieving under the applied load. Following this initial movement, the specimens began to creep. The rate-of-creep changed in some of the specimens as is seen in Table IX and can also be seen on Figures 46 through 57. Not all of the specimens failed, so this distinction has been indicated on individual figures.

From the creep rates and strains at 1000 hours of the 4-inch specimens given in Table IX, it appears at first glance that the Fiberglass Resources, Ceilcoat, and Bondstrand pipe behaved much better than the A. O. Smith and Koch samples. However, this effect is not because the pipes behave better in creep.

The loads placed on all specimens were a direct result of the values obtained from the manufacturer for the recommended working load. A load corresponding to the allowable load was placed on one specimen and the other specimens were more heavily loaded. For example, the test results on the 4-inch specimens show that the allowable load value on pipe from Fiberglass Resources is lower with respect to failure than the value from A. O. Smith. The Fiberglass Resources pipe would have a larger factor of safety in long term axial tension than the A. O. Smith specimens. However, a large factor of safety is not the only criteria to use in selecting the best material. An extremely large factor of safety would not be economical because much more material would be paid for than is necessary. The selection of material would depend on the loads that will have to be supported.

## TABLE IX

## CREEP RATES COMPUTED BY RADIAN

| Pipe | Size (in.) | Load (lbs.) | Time Span Used (hrs.) | Rate in./100 ft./yr. | Strain @ 1000 hrs. (in/in x $10^{3}$) |
|---|---|---|---|---|---|
| A. O. Smith | 6 | 5,100 | 300-1000 | 10 | 4.09 |
| | 6 | 7,140 | 300-1000 | 20 | 8.28 |
| | 6 | 9,180 | 400-1000 | 45 | 15.4 |
| | 6 | 11,220 | 300-500 | 320 | --- |
| | | | 700-880 | 180 | --- |
| | 4 | 2,200 | 300-1000 | 20 | 6.58 |
| | 4 | 2,640 | 300-1000 | 20 | 7.71 |
| | 4 | 3,520 | 400-1000 | 44 | 12.4 |
| | 4 | 4,400 | 200-400 | 210 | |
| | | | 600-1000 | 110 | 26.4 |
| | 4 | 5,280 | 45-100 | 810 | --- |
| | 4 | 6,600 | 1-3 | 22,000 | --- |
| Apex | 6 | 4,000 | 200-1000 | 2 | 2.95 |
| Bondstrand | 6 | 10,238 | 300-1000 | 4 | 2.70 |
| | 6 | 13,388 | 400-1000 | 10 | 4.22 |
| | 6 | 15,750 | 400-1000 | 15 | 5.55 |
| | 4 | 7,200 | 200-1000 | 7 | 2.90 |
| | 4 | 9,360 | 300-1000 | 7 | 4.00 |
| | 4 | 10,800 | 300-1000 | 14 | 5.40 |
| | 4 | 11,520 | 300-1000 | 12 | 5.05 |
| | 4 | 12,960 | 200-500 | 30 | --- |
| Ceilcoat | 6 | 7,000 | 300-1000 | 1 | 1.65 |
| | 6 | 12,000 | 300-1000 | 3 | 2.80 |
| | 6 | 16,000 | 300-1000 | 2 | 3.53 |
| | 4 | 3,000 | 300-1000 | 2 | 2.30 |
| | 4 | 4,425 | 300-1000 | 2 | 3.40 |
| | 4 | 8,000 | 300-1000 | 4 | 5.10 |
| | 4 | 10,000 | 300-1000 | 3 | 6.10 |

| Pipe | Size (in.) | Load (lbs.) | Time Span Used (hrs.) | Rate in./100 ft./yr. | Strain @ 1000 hrs. (in/in x $10^3$) |
|---|---|---|---|---|---|
| Ciba | 4 | 3,100 | 300-1000 | 4 | 2.03 |
| | 4 | 4,030 | 300-1000 | 5 | 2.70 |
| | 4 | 4,960 | 300-1000 | 5 | 3.15 |
| | 4 | 5,580 | 300-1000 | 5 | 3.73 |
| | 4 | 6,200 | 300-1000 | 6 | 3.65 |
| Fiberglass Resources | 6 | 11,400 | 400-1000 | 38 | 12.4 |
| | 6 | 12,600 | 70-150 | 240 | --- |
| | | | 225-334 | 150 | --- |
| | 6 | 15,000 | 10-24 | 1,500 | --- |
| | 6 | 13,800 | 95-306 | 248 | --- |
| | 4 | 5,250 | 600-1200 | 3 | 2.00 |
| | 4 | 5,900 | 400-1000 | 4 | 2.29 |
| | 4 | 6,560 | 400-1000 | 10 | 3.99 |
| | 4 | 7,220 | 400-1000 | 13 | 4.66 |
| | 4 | 8,600 | 300-1000 | 9 | 4.60 |
| | 4 | 9,925 | 300-1000 | 12 | 5.43 |
| Koch | 6 | 5,650 | 400-1000 | 37 | 10.18 |
| | 6 | 7,400 | 400-700 | 168 | 28.20 |
| | | | 800-1000 | 289 | --- |
| | 6 | 8,700 | 100-250 | 584 | --- |
| | 4 | 2,250 | 400-1000 | 7 | 4.00 |
| | 4 | 2,925 | 400-1000 | 8 | 4.95 |
| | 4 | 3,375 | 600-1000 | 13 | 5.50 |
| | 4 | 3,600 | 600-1000 | 20 | 7.75 |
| | 4 | 14,050 | 600-1000 | 18 | 8.18 |
| | 4 | 4,500 | 600-1000 | 28 | 13.20 |

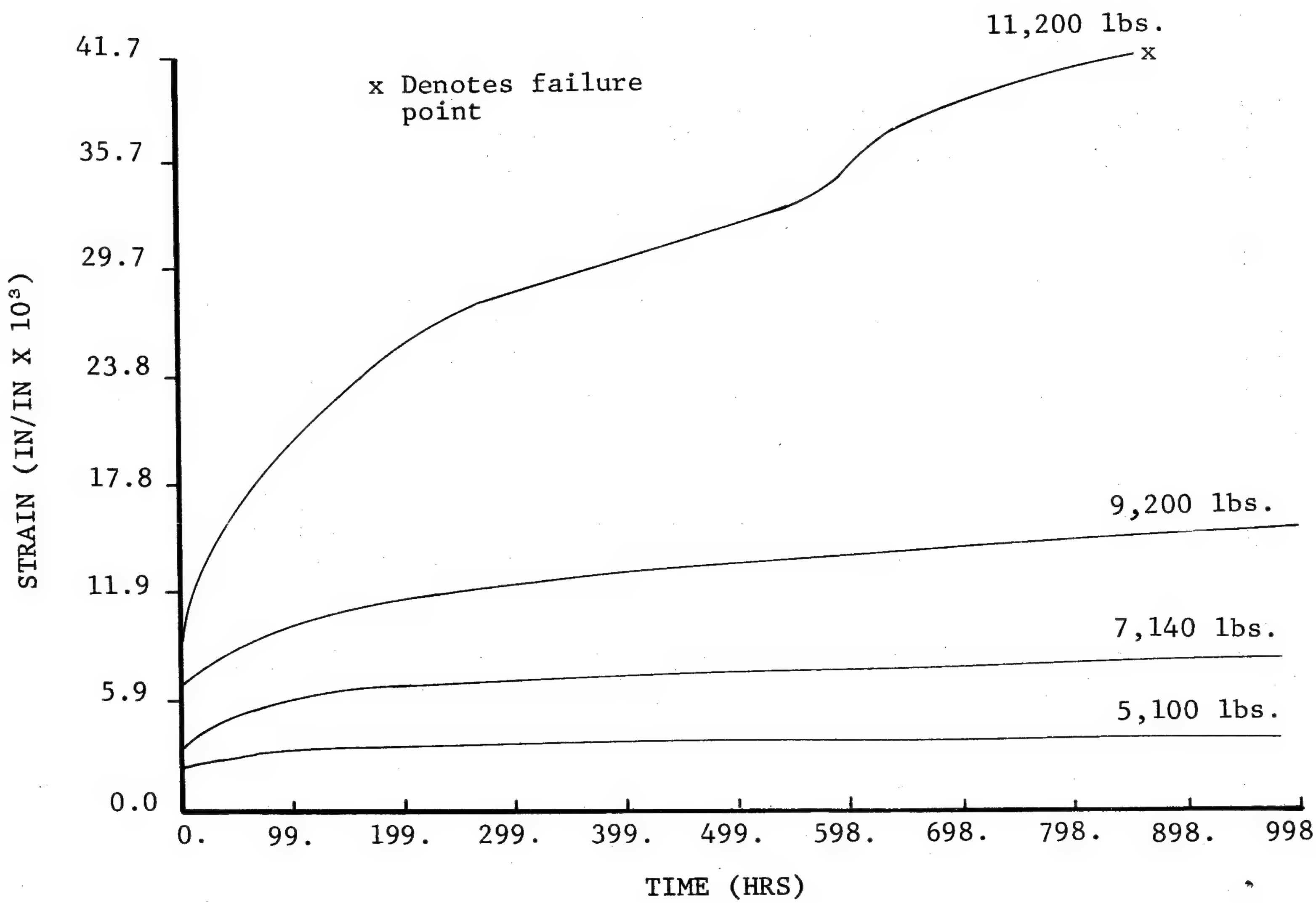



Figure 46. Creep Test A. O. Smith 6-inch Specimens

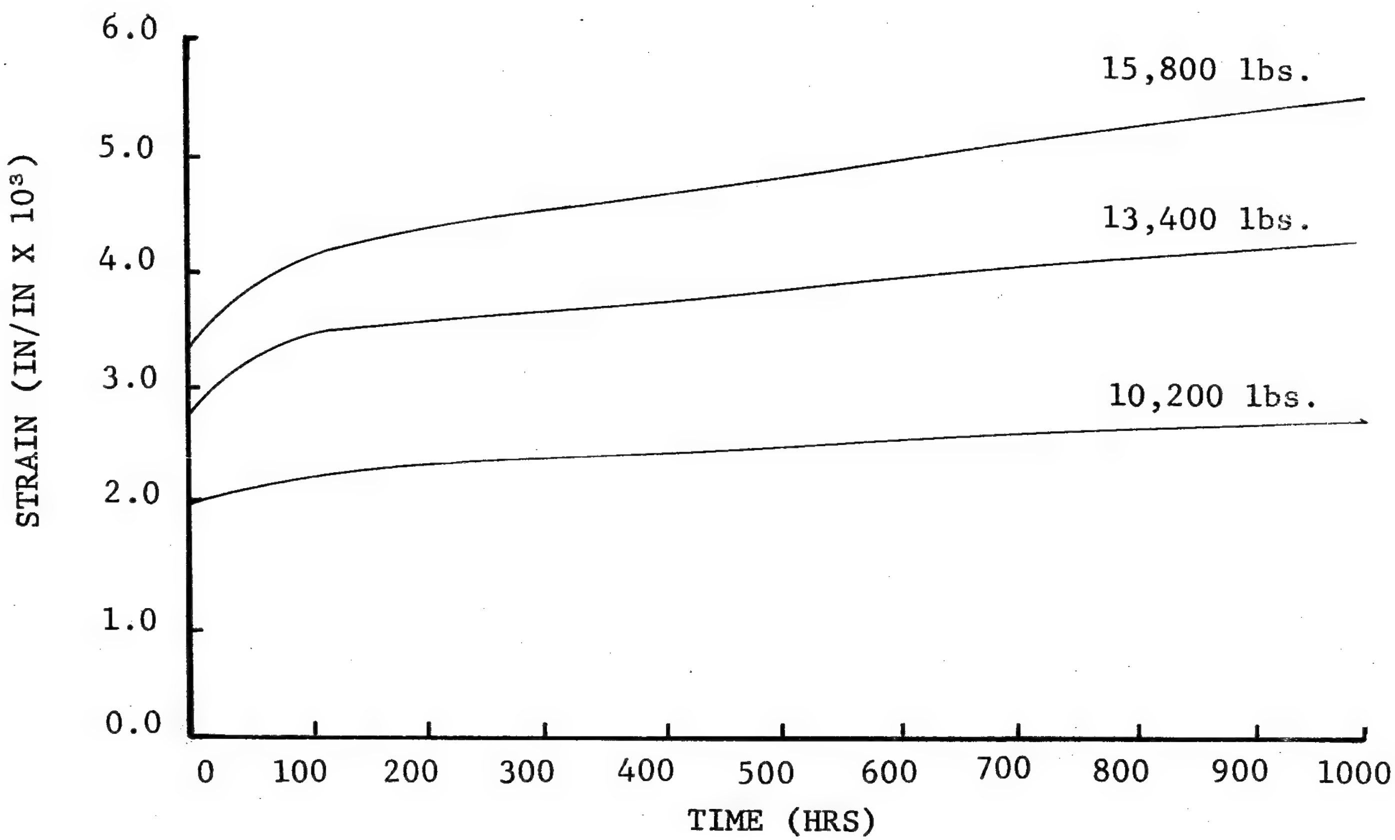



Figure 47. Creep Test Bondstrand 6-inch Specimens

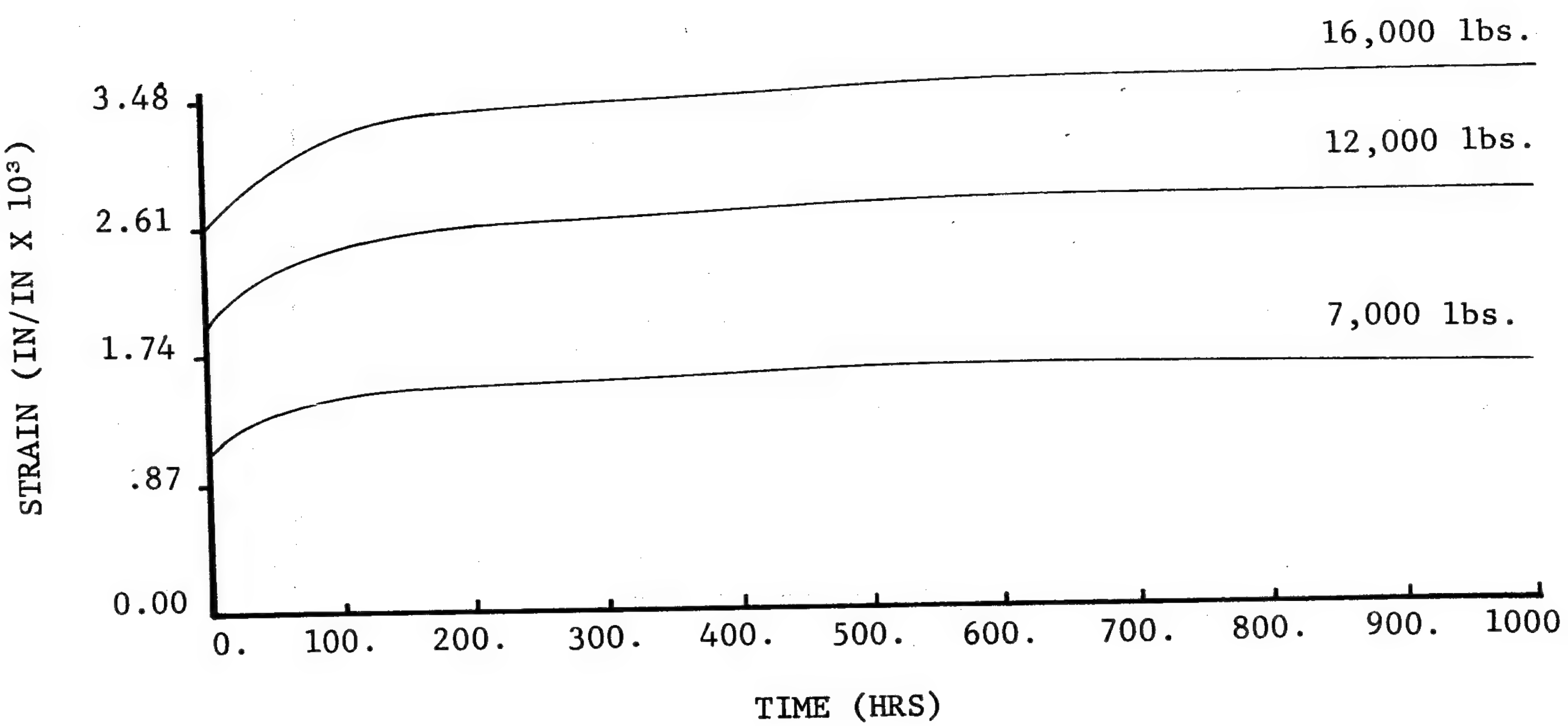



Figure 48. Creep Test Ceilcoat 6-inch Specimens

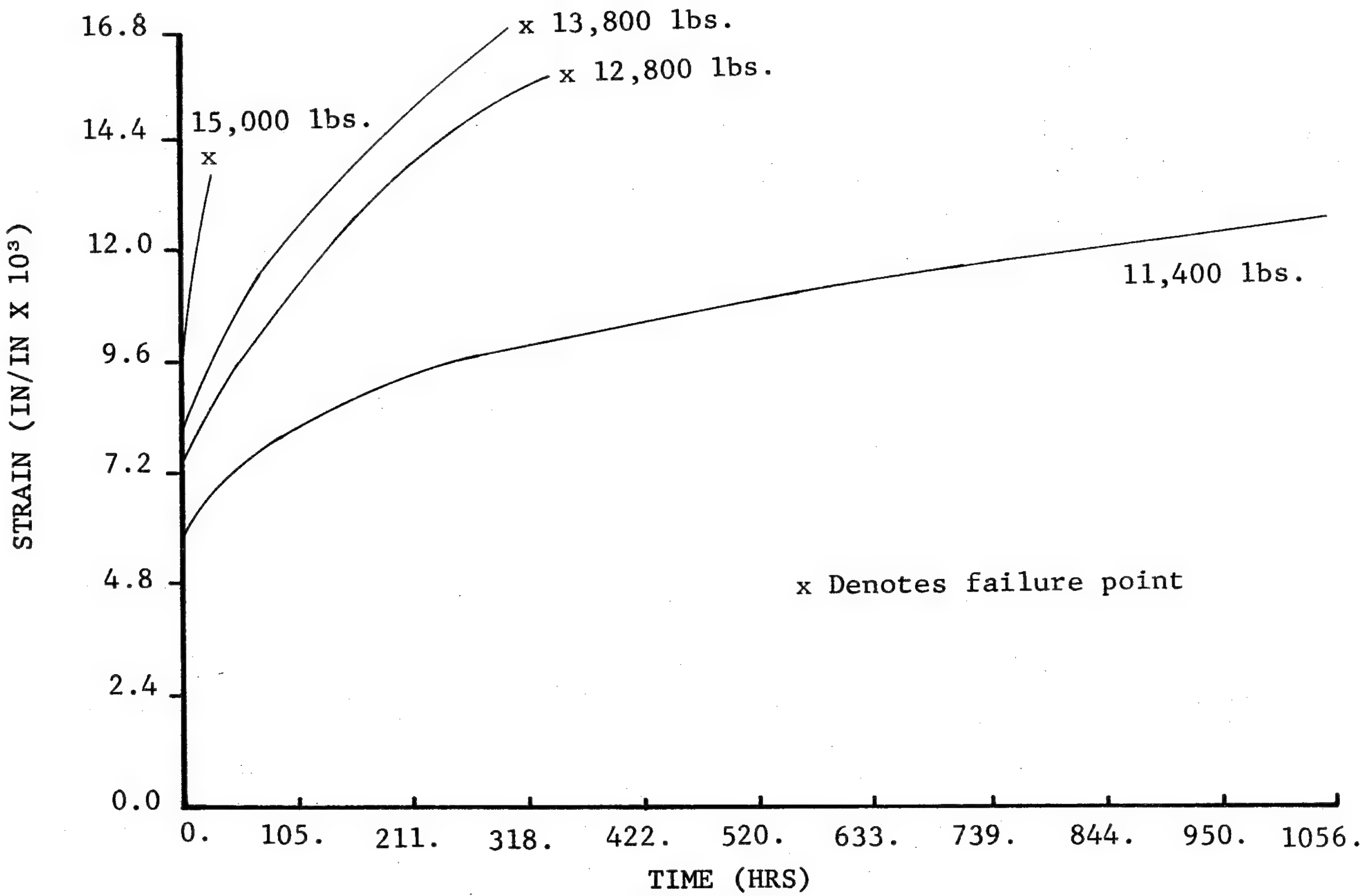



Figure 49. Creep Test Fiberglass Resources 6-inch Specimens

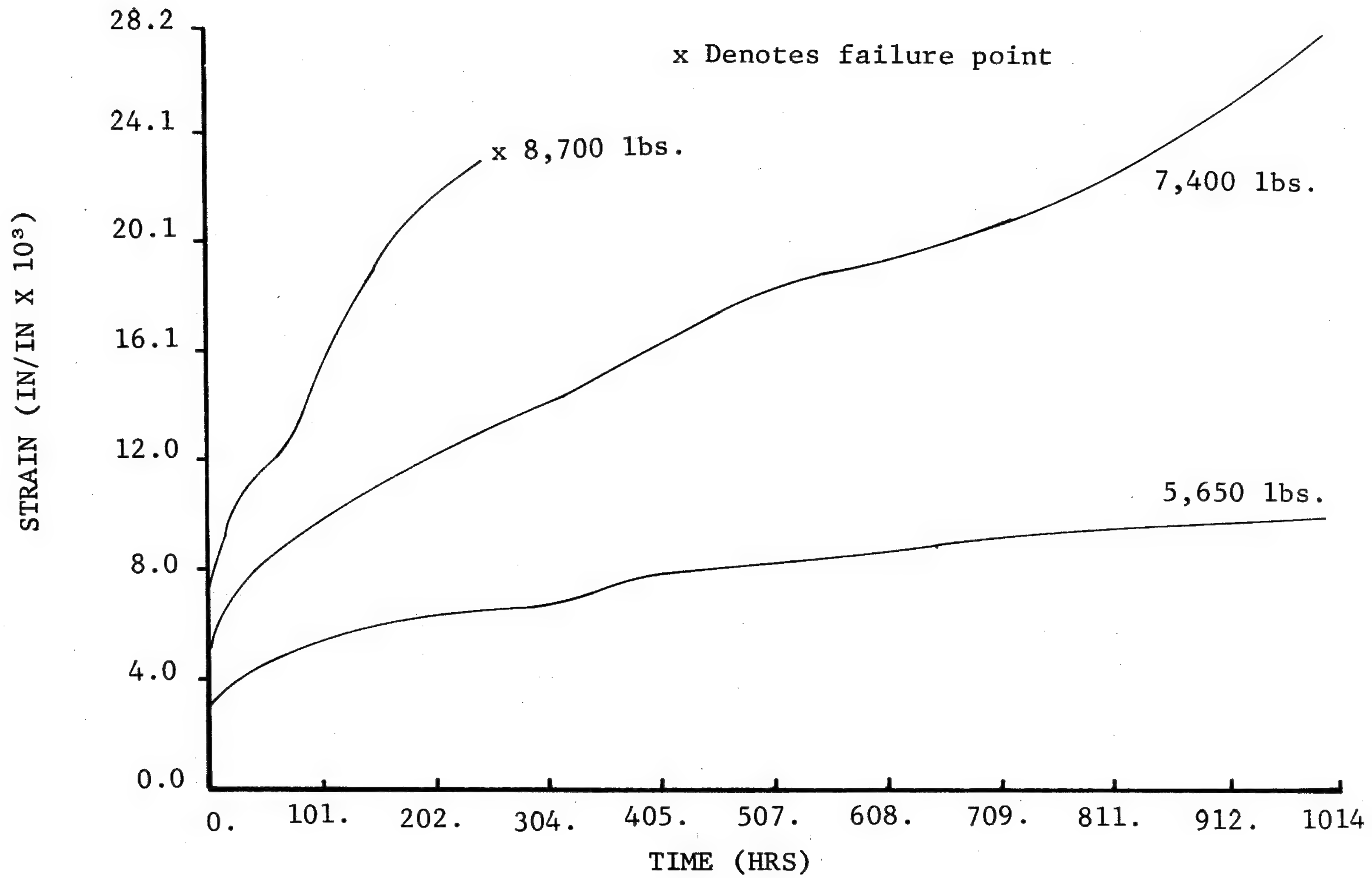



Figure 50. Creep Test Koch 6-inch Specimens

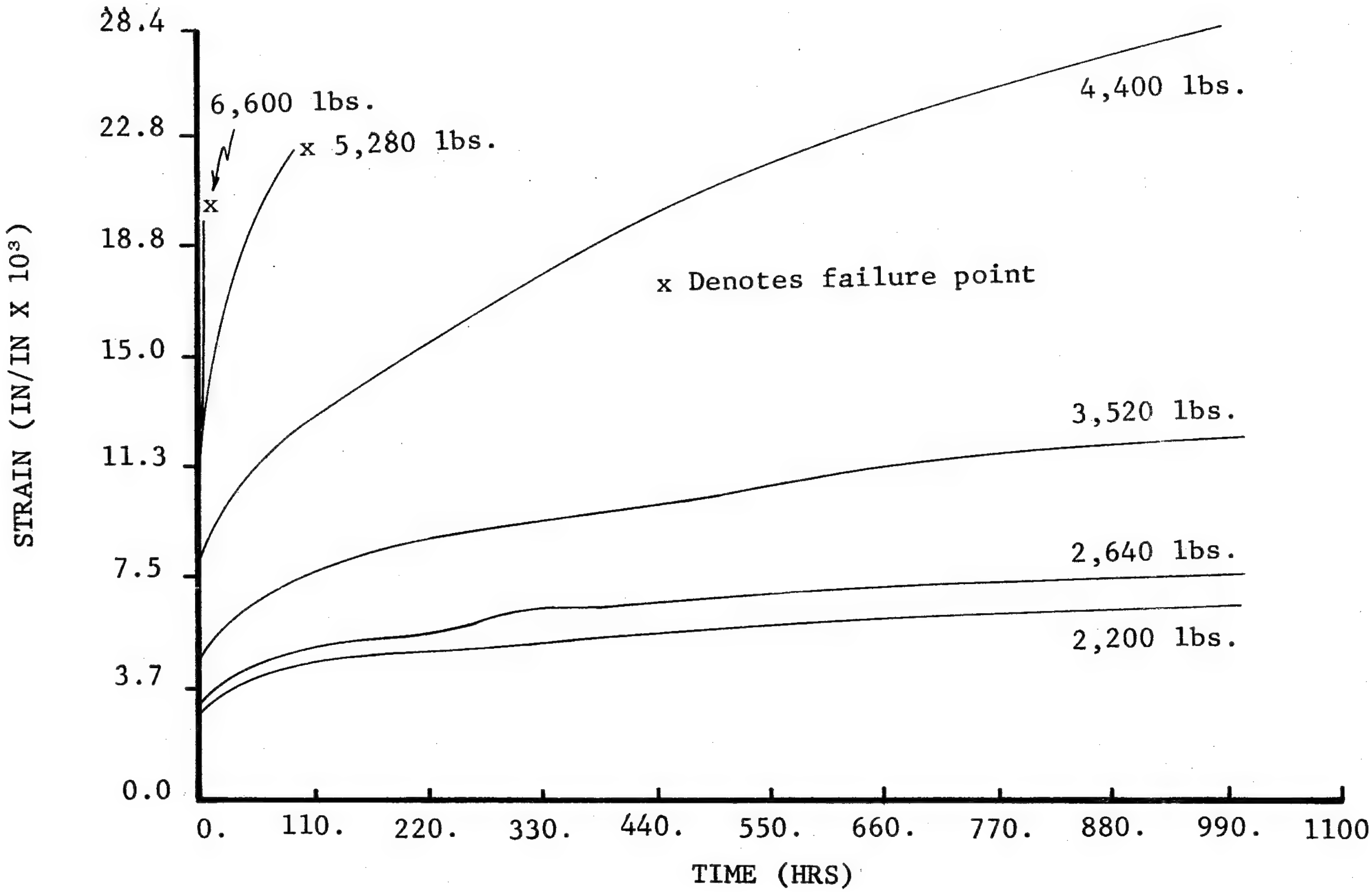



Figure 51. Creep Test A. O. Smith 4-inch Specimens

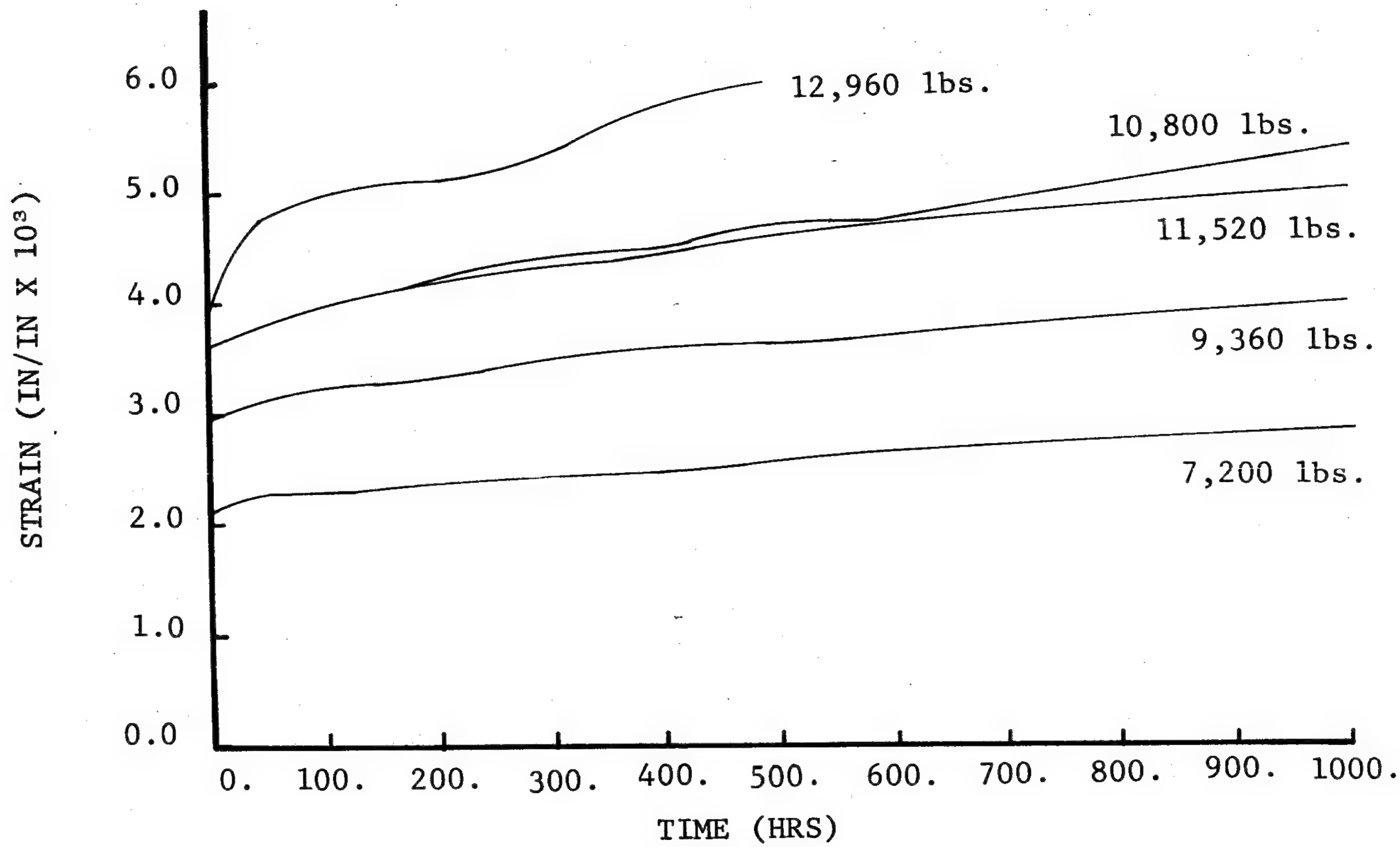



Figure 52. Creep Test Bondstrand 4-inch Specimens

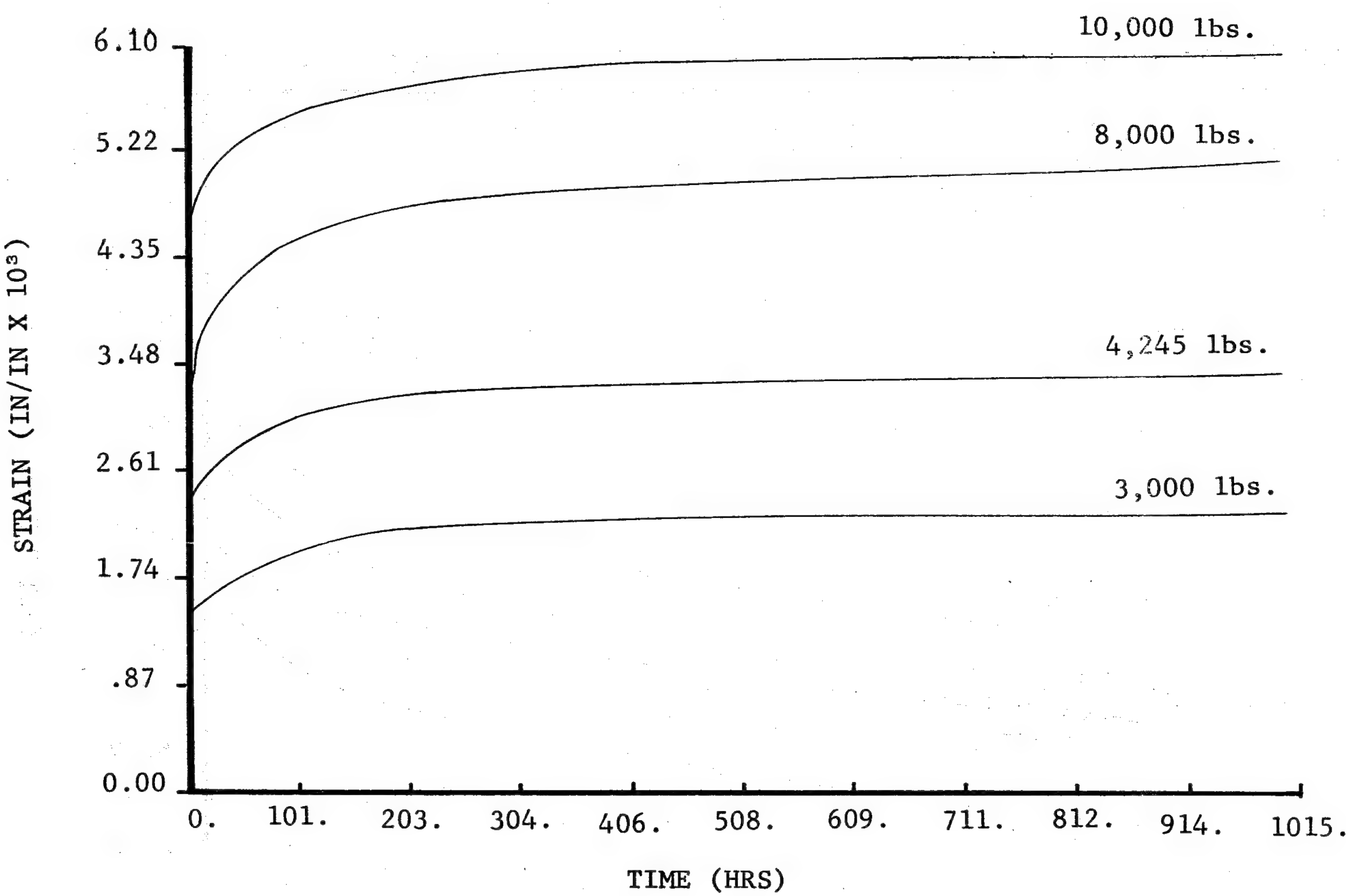



Figure 53. Creep Test Ceilcoat 4-inch Specimens

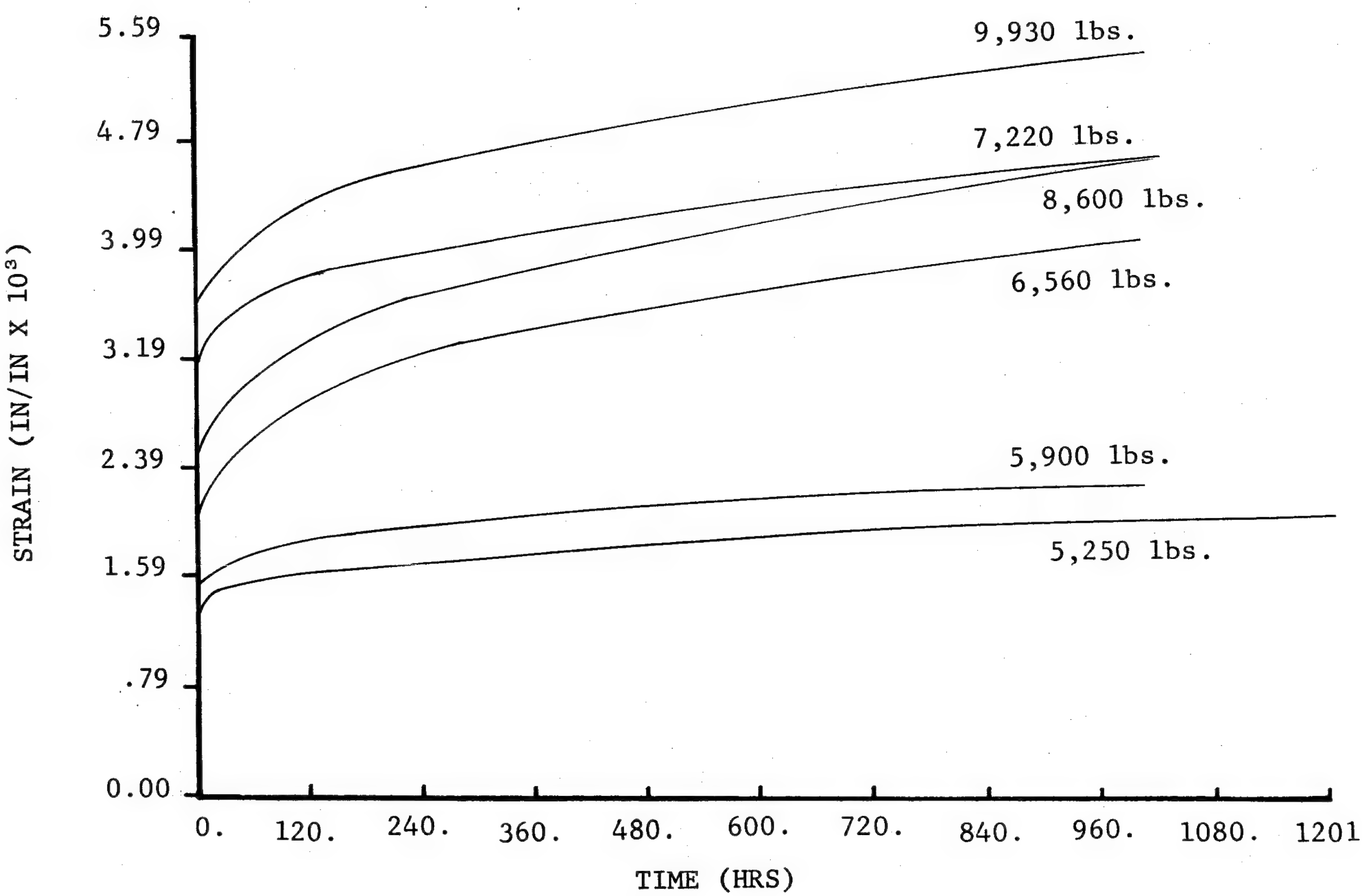



Figure 54. Creep Test Fiberglass Resources 4-inch Specimens

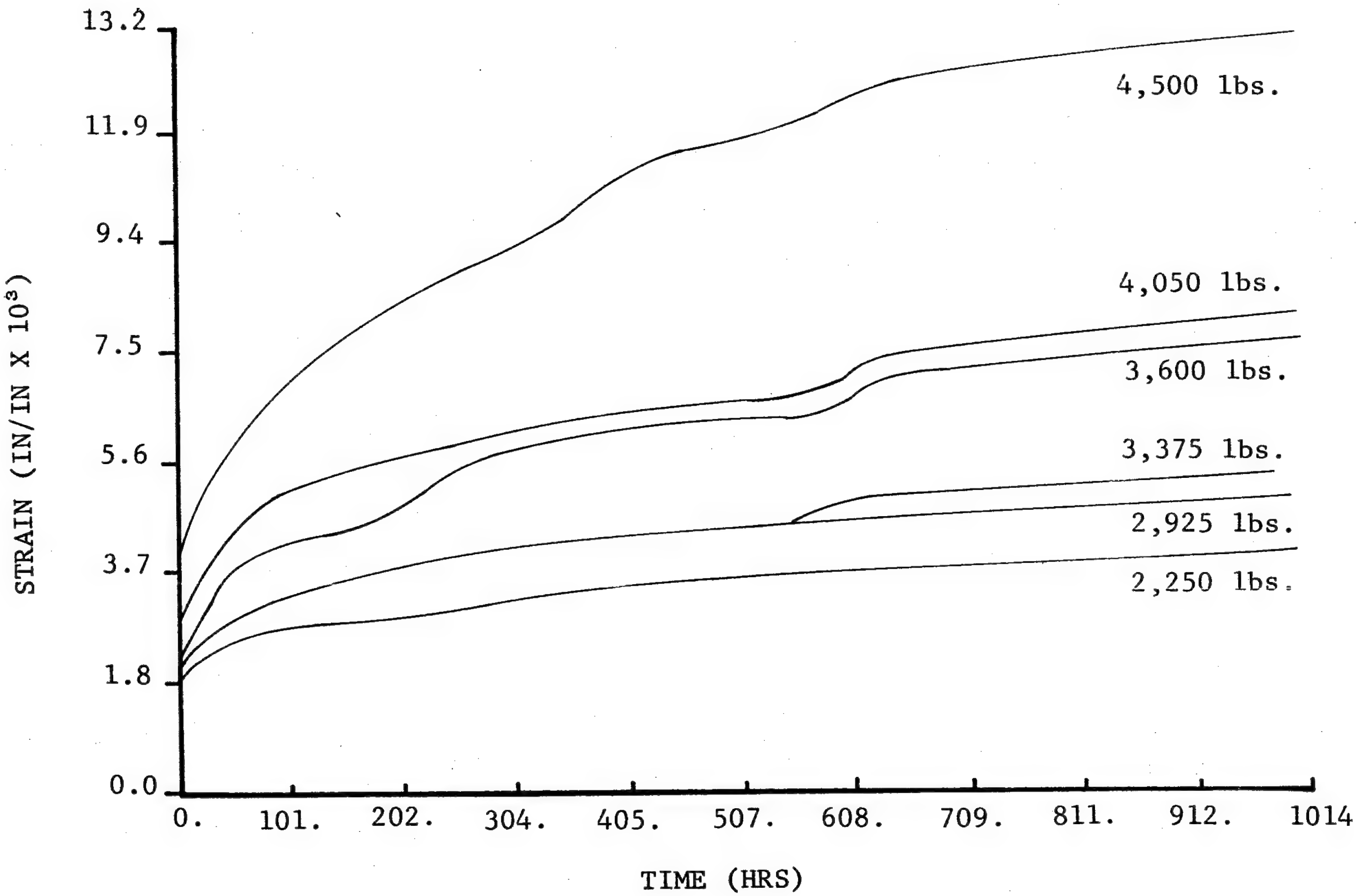



Figure 55. Creep Test Koch 4-inch Specimens

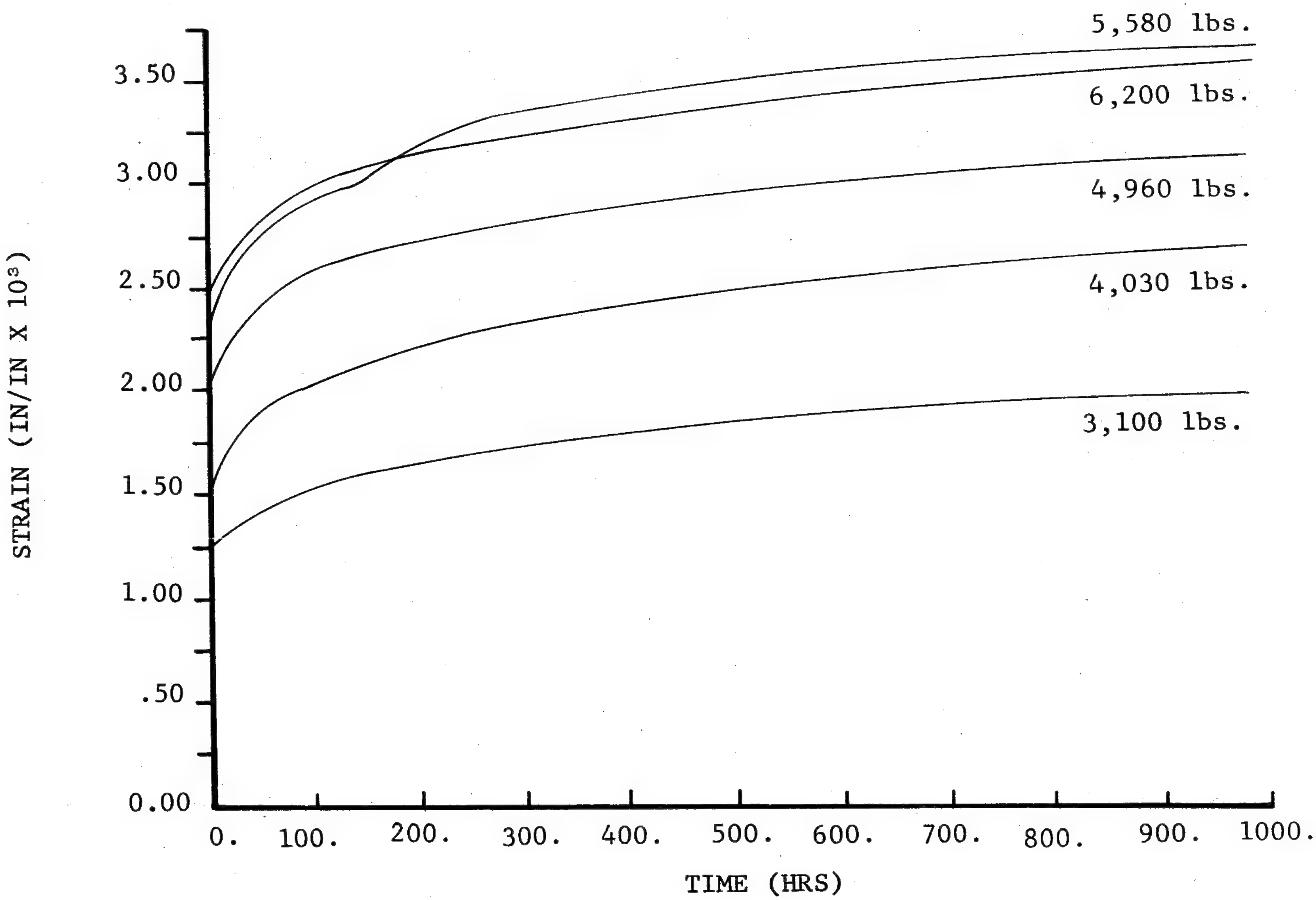



Figure 56. Creep Test Ciba 4-inch Specimens

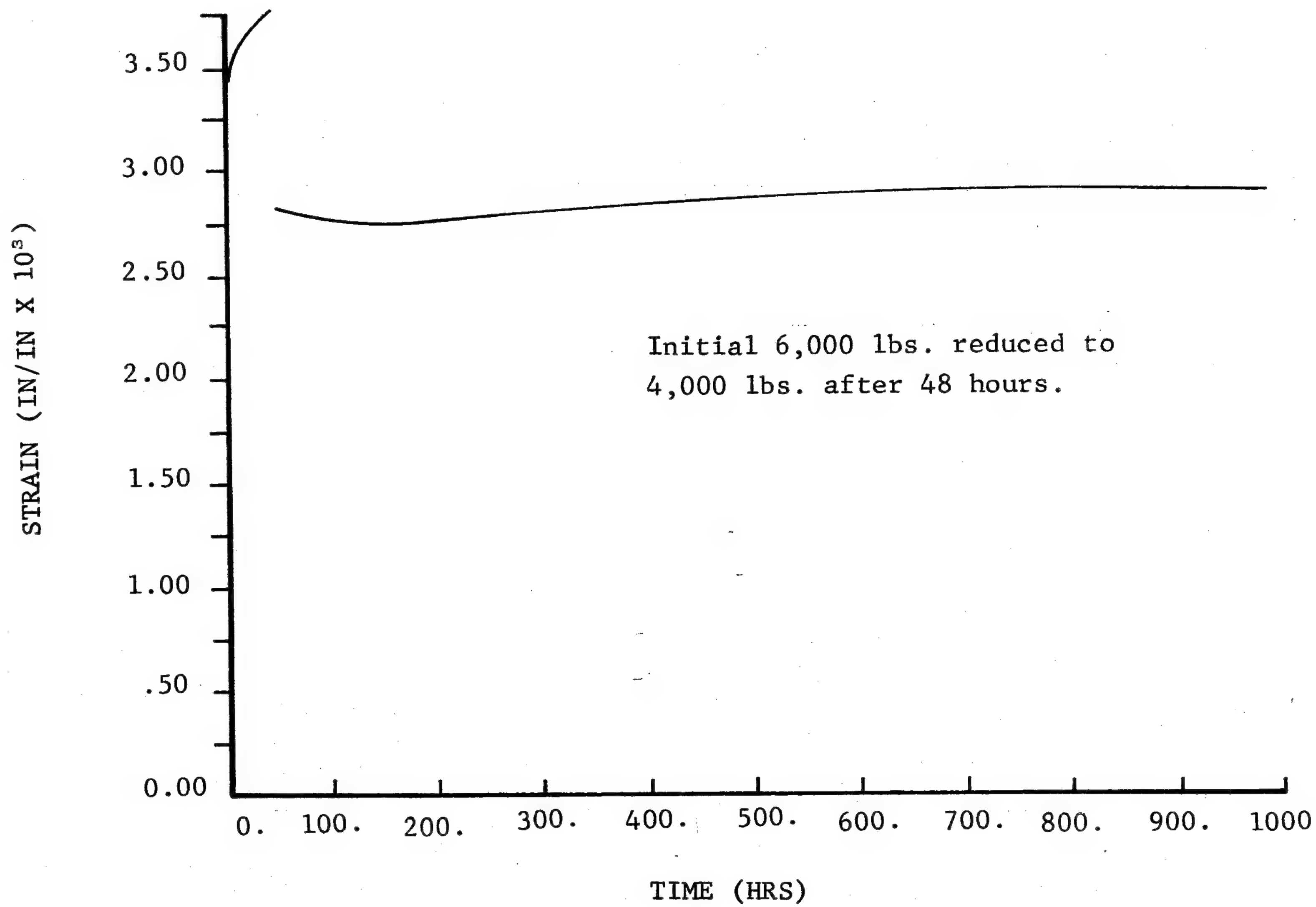



Figure 57. Creep Test Apex 6-inch Specimens

With this knowledge the pipe that combined a low cost, low creep rate, and a reasonable safety factor would be selected. This same type of analysis must also be applied to the 6-inch specimens.

On Figure 54 the Fiberglass Resources 4-inch pipe loaded at 8,600 lbs. and on Figure 52 the Bondstrand pipe loaded at 11,520 lbs. has a low creep rate when compared to the specimens with both higher and lower loads. It is hard to find an explanation for this deviation other than a difference in the pipe itself. If all the specimens were not taken from the same joint of pipe, it is possible that a heavier walled specimen was included in the test.

The Fibercast creep specimens were not tested because the flanges would not support a tensile load in the range of the tests. Therefore, no creep data will be available for Fibercast.

During the initial creep studies at Radian, it became obvious that temperature played an important role in the reaction of the specimens to long term loads. Irregularities were noticed when unexpected failures in the pipe caused a temporary change in the test temperature. Failures occurred in the pipe at stress levels much lower than those achieved in the tension test. This is partly because of the variation of total time and load, and partly because of the environment.

To determine the effect of temperature on the creep characteristics of the FRP pipe, the specimens from Fiberglass Resources were subjected to sustained loading at both 125°F and 75°F. The results of this comparison are shown in Table X. These very significant results indicate that at 75°F the materials are a great deal less susceptible to creep. To fully explain these results, an in-depth investigation of temperature effects would be necessary. These results were unexpected but very significant when one considers their possible impact on the

## TABLE X

## COMPARISON OF CREEP RATES OF FIBERGLASS RESOURCES 4-INCH PIPE AT TWO DIFFERENT TEMPERATURES

| Tensile Load (lbs.) | Creep Rate @ 75°F (in/100 ft/yr) | Creep Rate @ 125°F (in/100 ft./yr.) |
|---|---|---|
| 5250 | 0.81 | 3 |
| 5900 | 0.65 | 4 |
| 6560 | 0.65 | 10 |
| 7220 | 0.65 | 13 |
| 8600 | 0.81 | 9 |
| 9925 | 0.81 | 12 |

use of FRP subjected to sustained loads and temperature cycling. The Military Specification (MIL-P-22245A, DOCKS) defines 150°F as the highest temperature capability for fiberglass reinforced plastic. This is a significant fact to keep in mind because the creep results were obtained at 125°F. It is expected that a more dramatic creep rate would be identified in the 150°F range.

The fact that there are drastic changes in the physical properties of polymers with changes in temperature is well known. The interesting point is that apparently the change for this thermoset plastic is at a low temperature. These properties alluded to above are the glass transition temperature, $T_g$, and heat distortion temperature, $T_d$. The term glass transition refers to the characteristic change in polymer properties from those of a relatively hard, brittle, glassy material to those of a softer, more flexible, rubbery substance as the temperature is raised through the glass transition temperature $T_g$. Although $T_g$ is not known for this material, the changes in creep characteristics are probably not due to $T_g$ but to the heat distortion temperature $T_d$. The heat distortion temperature, $T_d$, is the temperature at which there is a certain deflection in a beam composed of the material when a constant load is applied to one end and while the other end is rigidly fixed. $T_d$ is related to the degree of cross-linking in the polymer, i.e., the greater the degree of cross-linking, the higher the distortion temperature. Since $T_d$ is related to the degree of cross-linking, it is expected that all pipe samples will have varying distortion temperatures.

F. Creep Test Followed by a Tension Test

The results of this combination test indicate how long-term loads affect the tensile strength of FRP pipe. The pipe was creeped at various loads and then the ultimate tensile

strength was determined. Table XI presents the history of the creeped pipe, its tensile strength and compares this data to the ultimate tensile strength of plain pipe. The tensile strengths of the creeped pipe are slightly higher than the noncreeped pipe strengths in some instances. Because of the length limitations imposed by sectioning the creeped pipe, the specimens for this test were 24 inches in length and the noncreeped specimens were 30 inches in length. Considering this point, it can be seen that at low creep loads the tensile strength is not affected, but as higher creep loads are reached the tensile strength may decrease approximately 20% of the original strength. An important point to be gained from this test is that for a creep load of less than one-fourth the tensile strength, the axial strength of creeped pipe does not decrease. This information is important because many designers use a safety factor of four. The test lends support that a safety factor of four is useful.

The creeped pipe specimens of both the Apex 6-inch pipe and Ceilcoat 4-inch pipe did not visually appear to be the same pipe as the pipe submitted for the tensile tests. Upon sectioning the creep specimens it appeared that the wall thicknesses were thinner than the samples submitted for tensile testing. The variation in the Apex pipe did not seem to affect the axial tensile strength. The Ceilcoat 4-inch pipe was only about 35% as strong in tension as its plain pipe. The difference in pipe greatly affected the results for this test.

The Fibercast specimens could not be tested because their flanges were not strong enough to allow creep testing. Only one Apex specimen could be tested because all other flanges were not strong enough to withstand these tensile forces. Ciba did not submit 6-inch specimens for creep testing.

TABLE XI

TENSILE STRENGTHS OF CREEPED PIPE*

| Pipe | Inch | Creep Load | Hours Creeped | Tensile Strength** of Noncreeped Pipe | Tensile Strength of Creeped Pipe |
|---|---|---|---|---|---|
| A. O. Smith | 4 | 2,200 | 1008 | 8,590 | 9,100 |
| | | 2,640 | 1008 | 8,590 | 9,700 |
| | | 3,520 | 1008 | 8,590 | 9,300 |
| | | 4,400 | 96 | 8,590 | 8,500 |
| | | 5,280 | 100 | 8,590 | 8,500 |
| | | 6,600 | 3 | 8,590 | 8,700 |
| | 6 | 5,100 | 998 | 19,600 | 21,000 |
| | | 7,140 | 998 | 19,600 | 20,000 |
| | | 9,180 | 998 | 19,600 | 20,500 |
| | | 11,200 | 864 | 19,600 | 19,500 |
| Apex | 6 | 4,000 | 1000 | 28,500 | 21,800 |
| Bondstrand | 4 | 7,200 | 1005 | 23,500 | 19,700 |
| | | 9,360 | 1000 | 23,500 | 22,400 |
| | | 10,800 | 1005 | 23,500 | 21,800 |
| | | 11,500 | 1008 | 23,500 | 21,200 |
| | | 13,000 | 528 (Flange Failed) | 23,500 | 20,900 |
| | | 14,000 | .1 (Flange Failed) | 23,500 | 23,400 |
| | 6 | 10,200 | 1000 | 36,200 | 33,700 |
| | | 13,300 | 1000 | 36,200 | 32,700 |
| | | 15,800 | 1000 | 36,200 | 32,000 |
| Ceilcoat | 4 | 3,000 | 1016 | 29,500 | 8,300 |
| | | 4,430 | 1016 | 29,500 | 9,600 |
| | | 8,000 | 1015 | 29,500 | 6,900 |
| | | 10,000 | 1013 | 29,500 | 9,900 |
| | | 12,000 | 0.1 | 29,500 | 8,100 |
| | 6 | 7,000 | 1016 | 60,100 | 59,500 |
| | | 12,000 | 1015 | 60,100 | 60,500 |
| | | 16,000 | 1015 | 60,100 | 56,000 |
| Ciba | 4 | 3,100 | 1000 | 36,000 | 22,200 |
| | | 4,030 | 1000 | 36,000 | 24,500 |
| | | 5,580 | 1000 | 36,000 | 24,400 |
| | | 6,200 | 1000 | 36,000 | 24,200 |
| Fiberglass Resources | 4 | 5,250 | 1201 | 24,300 | 28,800 |
| | | 5,900 | 1009 | 24,300 | 28,900 |
| | | 6,560 | 1009 | 24,300 | 25,700 |
| | | 7,220 | 1009 | 24,300 | 26,300 |
| | | 8,600 | 1029 | 24,300 | 21,000 |
| | 6 | 11,400 | 1104 | 22,700 | 25,000 |
| | | 12,600 | 334 (Flange Failed) | 22,700 | 24,200 |
| | | 13,800 | 1104 | 22,700 | 25,000 |
| Koch | 4 | 2,250 | 1014 | 12,000 | 12,500 |
| | | 3,380 | 1010 | 12,000 | 12,500 |
| | | 3,600 | 1010 | 12,000 | 11,400 |
| | | 4,050 | 1010 | 12,000 | 12,300 |
| | | 4,500 | 1010 | 12,000 | 12,200 |
| | 6 | 5,650 | 1014 | 15,500 | 15,500 |
| | | 7,400 | 1013 | 15,500 | 12,500 |

* All strengths and loads listed in pounds

**Thirty-inch specimens of noncreep pipe were tested in tension, whereas 24-inch specimens were used for the creeped pipe tension tests.

G. Creep Test Followed by a Tup Test

This combination test indicates what effects long-term loads and water have upon FRP pipe. Table XII gives the ultimate tup load and the deflection at this load for creeped pipe of known history. Generally, the pipe exhibited the load deflection pattern as shown in Figure 38 where the load rises with continued deflection until the ultimate is reached. At that point the load drops off rapidly with increased deflection. The only pipe that shows a marked decrease in the ultimate strength with increased creep load is the Koch pipe. For the Koch pipe when the creep load reaches one-third to one-fourth the ultimate tensile load the tup load ultimate decreases by about 40%. It is possible that the glass matrix was weakened by the long-term load. The tup ultimate for Koch pipe appears to be affected more by the creep load than the tensile strength (Table XI). The A. O. Smith tup ultimate also decreases with increasing creep load as did the tensile strength. Again, the tup ultimate appears to be more affected than the tensile ultimates. The Bondstrand 4-inch and the Fiberglass Resources 4-inch tup ultimates did not seem to be affected by the creep load as did the tensile load. These results suggest that the mechanism by which tensile strength is affected is different from the mechanism that affects tup strength.

The Ceilcoat 4-inch and 6-inch pipe should have approximately the same wall thickness. From previous cases all other factors being the same, the smaller diameter pipe should be stronger in point loading as compared to the larger diameter pipe. The Ceilcoat 4-inch creeped pipe was weaker in point loading than the 6-inch pipe. This gives additional support to the assumption that the 4-inch creeped pipe had different manufactured walls than did the specimens submitted for tensile testing.

TABLE XII

RESULTS FOR CREEP TEST FOLLOWED BY A TUP TEST*

| Pipe | (In) | Creep Load | Hours Creeped | Ultimate Tup Load | Deflection @ Ultimate Load (in.) |
|---|---|---|---|---|---|
| A. O. Smith | 4 | 2,200 | 1008 | 335 | 0.58 |
| | | 2,640 | 1008 | 325 | 0.57 |
| | | 3,520 | 1008 | 275 | 0.55 |
| | | 5,280 | 100 | 300 | 0.51 |
| | | 6,600 | 3 | 400 | 0.77 |
| | 6 | 5,100 | 998 | 525 | 0.61 |
| | | 7,140 | 998 | 575 | 0.76 |
| | | 9,180 | 998 | 430 | 0.89 |
| | | 11,200 | 864 | 400 | 0.62 |
| Apex | 6 | 4,000 | 1000 | 880 | 0.47 |
| Bondstrand | 4 | 7,200 | 1005 | 1,225 | 0.69 |
| | | 9,360 | 1000 | 1,320 | 0.89 |
| | | 10,800 | 1050 | 1,240 | 0.64 |
| | | 11,500 | 1008 | 1,160 | 0.63 |
| | | 13,000 | 528 (Flange Failed) | 1,300 | 0.70 |
| | | 14,000 | .1 (Flange Failed) | 1,280 | 0.62 |
| | 6 | 10,000 | 1000 | 1,305 | 0.73 |
| | | 13,300 | 1000 | 1,300 | 0.70 |
| | | 15,800 | 1000 | 1,265 | 0.78 |
| Ceilcoat | 4 | 3,000 | 1016 | 1,000 | 0.20 |
| | | 4,430 | 1016 | 1,150 | 0.22 |
| | | 8,000 | 1015 | 1,250 | 0.23 |
| | | 10,000 | 1013 | 1,000 | 0.23 |
| | | 12,000 | 0.1 (Flange Failed) | 1,380 | 0.33 |
| | 6 | 7,000 | 1016 | 1,450 | 0.34 |
| | | 12,000 | 1015 | 1,540 | 0.36 |
| | | 16,000 | 1015 | 1,605 | 0.36 |
| Ciba | 4 | 3,100 | 1000 | 385 | 0.55 |
| | | 4,030 | 1000 | 500 | 0.78 |
| | | 4,960 | 1000 | 495 | 0.72 |
| | | 5,580 | 1000 | 420 | 0.53 |
| | | 6,200 | 1000 | 415 | 0.55 |
| Fiberglass Resources | 4 | 5,250 | 1201 | 1,375 | 0.39 |
| | | 5,900 | 1009 | 1,440 | 0.43 |
| | | 7,200 | 1009 | 1,325 | 0.37 |
| | | 8,600 | 1029 | 1,375 | 0.39 |
| | 6 | 11,400 | 1104 | 640 | 0.54 |
| | | 12,600 | 334 (Flange Failed) | 675 | 0.52 |
| Koch | 4 | 2,250 | 1014 | 885 | 1.1 |
| | | 2,925 | 1014 | 945 | 1.2 |
| | | 3,380 | 1010 | 500 | 0.50 |
| | | 3,600 | 1010 | 590 | 0.61 |
| | | 4,050 | 1010 | 580 | 0.64 |
| | | 4,500 | 1010 | 690 | 0.75 |
| | 6 | 5,650 | 1014 | 720 | 1.2 |
| | | 7,400 | 1013 | 450 | 0.93 |

* All loads listed in pounds.

The Fibercast creep specimens could not be creep tested and data for these specimens cannot be given. Ciba did not submit any 6-inch specimens for the creep test. Only one Apex pipe could be tested because all the other flanges they supplied would not hold the tensile load.

H. Fifty Percent Point Load Followed by a Creep Test

The results of this combination test give an indication whether a potential weak spot would significantly affect the life of the water well system. If the pipe were damaged during installation, the long-term life of the well could be seriously affected.

Samples of all available specimens were first tupped to 50% of the ultimate tup strength. These pipes were then creeped tested to observe their performance over a long period. The selected creep loads were 20% to 30% of the ultimate tensile strength of the pipe. In addition, loads were selected so that their creep rates could be compared with the creep rates of the plain creeped pipe. Because the flanges of the Apex pipe would not support a load in the selected range, the reduced load of 4,000 lbs. was selected.

The amount of damage a 50% point load does to the pipe varies with the brand of pipe. As shown in Table XIII this tup load deflection is less than 0.10 inch except for the Ciba and Koch pipe. Both the Ciba and Koch pipe exhibited more damage by the 50% tup load than the other brands tested.

None of the pipes failed during the creep testing. Table XIII presents the creep rates of the point loaded pipe and the creep rates of the plain pipe. In every case but the Koch and Apex pipe the rates are approximately the same and the stain at

## TABLE XIII

### COMPARISON OF THE CREEP RATES FOR PLAIN AND FIFTY PERCENT POINT LOADED PIPE

| Pipe | Size (in) | Creep Load (lbs) | 50% Point Load (lbs) | Tup Deflection (in) | Time Span Used for Rate (hrs) | Rate (in/100 ft/yr) | Strain @ 1000 hrs (in/in x $10^{-3}$) |
|---|---|---|---|---|---|---|---|
| Plain Apex | 6 | 4,000 | | | 200-1000 | 2 | 2.95 |
| Tupped Apex | 6 | 4,000 | 420 | 0.08 | 200- 600 | 7 | ---- |
| | | | | | 600-1000 | 2 | 4.63 |
| Plain Bondstrand | 4 | 7,200 | | | 200-1000 | 7 | 2.90 |
| Tupped Bondstrand | 4 | 7,200 | 600 | 0.05 | 300-1000 | 8 | 3.80 |
| Plain Bondstrand | 6 | 10,200 | | | 300-1000 | 4 | 2.70 |
| Tupped Bondstrand | 6 | 10,200 | 650 | 0.08 | 300-1000 | 6 | 3.00 |
| Plain Ceilcoat | 4 | 8,000 | | | 300-1000 | 4 | 5.10 |
| Tupped Ceilcoat | 4 | 8,000 | 550 | 0.07 | 300-1000 | 4 | 4.25 |
| Plain Ceilcoat | 6 | 12,000 | | | 300-1000 | 3 | 2.80 |
| Tupped Ceilcoat | 6 | 12,000 | 750 | 0.08 | 300-1000 | 4 | 3.10 |
| Plain Ciba | 4 | 6,200 | | | 300-1000 | 6 | 3.65 |
| Tupped Ciba | 4 | 6,200 | 240 | 0.20 | 300-1000 | 8 | 4.25 |
| Plain Koch | 6 | 5,650 | | | 400-1000 | 7 | 4.00 |
| Tupped Koch | 6 | 5,650 | 360 | 0.38 | 400-1000 | 14 | 7.65 |

1000 hours was comparable. The Apex pipe exhibited a large rate during the first 600 hours and after that time the rate diminished to the plain pipe rate. The Koch pipe's rate approximately doubled as did its strain at 1000 hours.

From the data it appears that for the stiff pipe or that pipe which must resist the tup point, the creep properties are not greatly affected. These relatively thick walled pipes show little or no wall damage after 50% point loading. In the well design it would be important to ensure against premature failure and these thicker walls should be considered.

However, the pipe which showed the least affect to the 50% tup loading is not necessarily the best pipe since each pipe can ultimately withstand different ultimate tup loads. This data does indicate how much of the ultimate tup strength could be effectively used over long periods of time.

I. Tup Test Followed by a Tension Test

In this test, specimens are first tup tested and then are tested for their tensile strength. The purpose of this test is to simulate a rock piercing the pipe wall or a weak spot and determining the ability of the pipe to localize a failure. This decrease in strength would be important if it were attempted to pull the casing and in some instances if the casing were weakened severely enough a failure might be propagated causing the well casing to separate. Table XIV compared the average tensile strength of plain and tupped pipe. As shown the strengths can decrease by as much as 60%. In general, the large diameter pipe loses more strength from being tupped. The probable reason is that for the larger diameter pipes a larger and more severe puncture was imposed by the tup test.

TABLE XIV

AVERAGE TENSILE STRENGTHS OF TUPPED PIPE COMPARED TO PLAIN PIPE STRENGTHS*

| Pipe | 8-inch | | 10-inch | |
|---|---|---|---|---|
| | Plain Pipe | Tupped Pipe | Plain Pipe | Tupped Pipe |
| A. O. Smith | 37,400 | 24,300 | 51,000 | 27,600 |
| Apex | 53,100 | 24,700 | 88,300 | 37,500 |
| Bondstrand | 57,200 | 52,200 | 71,500 | 51,700 |
| Brunswick | 80,800 | 58,500 | 98,400 | 62,700 |
| Ceilcoat | 91,500 | 57,800 | 106,400 | 87,700 |
| Fibercast | 122,000 | 44,800 | --- | --- |
| Fiberglass Resources | 51,300 | 40,900 | 62,900 | 40,000 |
| Koch | 32,500 | 23,700 | --- | --- |

* All strengths listed in pounds.

In all cases the failure plane in the tension test passed through the tup hole. Generally, the failure plane was perpendicular to the pipe axis. The actual strength of each pipe previously tupped varies considerably because each tup hole is oriented differently and is of a different size.

With exception of the Ceilcoat pipe the filament wound pipe appears to be affected less than the other types of pipe. In many instances the fibers of the filament wound pipe were not torn or broken and still could help support the load.

## SECTION VI

## APPLICATION OF THE TEST RESULTS TO WATER WELL SYSTEMS

The casing pipe must be able to support its own weight and possibly a much greater but unknown tensile load if it were pulled. Table XV gives the maximum length of pipe that could support its own weight on the basis of the tensile and coupling strengths. With this information, a safety factor, and well design information, candidate materials can be selected. From the results of the tup and parallel plate tests candidate materials can be further limited on the basis of expected formation pressures. It has been estimated and proven by experience that some fiberglass casing has collapse strengths great enough to withstand radial pressures.

From the data from the tup test followed by a tension test a further restricting parameter can be put on the candidate materials. If the casing is to be pulled, this information would be important in determining the safety factor.

The well screen materials must resist the radial pressures of the gravel pack and from the data of the hydrostatic tests the strengths are shown to be highly variable. Again, FRP screens have been used and have withstood the pressures. The Radian tests show the relative strengths of the candidate materials.

The column pipe must be able to support its own weight, the column of water, the pump, initially the shaft, and other miscellaneous parts. In addition, the pipe must be capable of resisting the pressures at the bottom of the column. Table XVI gives the maximum length of column pipe based on the ultimate tensile properties of the pipe and the couplings. Using the appropriate safety factor, candidate materials could be selected.

TABLE XV

MAXIMUM LENGTHS OF CASING PIPE

| Pipe | Diameter (Inches) | Maximum Self-Supporting Length (Ft.) Based Upon Pipe Strength | Coupling Strength |
|---|---|---|---|
| A. O. Smith | 8 | 12,500 | 12,100 |
| | 10 | 10,900 | 11,300 |
| Apex | 8 | 8,560 | 6,710 |
| | 10 | 9,600 | 2,750 |
| Bondstrand | 8 | 14,300 | 11,900 |
| | 10 | 13,000 | 9,490 |
| Brunswick | 8 | 19,700 | 11,200 |
| | 10 | 19,300 | 12,700 |
| Ceilcoat | 8 | 17,300 | 12,000 |
| | 10 | 13,300 | 10,200 |
| Fibercast | 8 | 22,500 | 16,000 |
| Fiberglass Resources | 8 | 10,700 | 8,100 |
| | 10 | 10,700 | 6,100 |
| Koch | 8 | 16,300 | 16,400 |

## TABLE XVI

## MAXIMUM LENGTHS OF COLUMN PIPE*

| Pipe | Diameter (Inches) | Maximum Self-Supporting Length (Ft.) Based Upon Pipe Strength | Maximum Self-Supporting Length (Ft.) Based Upon Coupling Strength |
|---|---|---|---|
| A. O. Smith | 4 | 500 | 493 |
| | 6 | 793 | 806 |
| Apex | 6 | 1,080 | 467 |
| Bondstrand | 4 | 1,320 | 1,280 |
| | 6 | 1,410 | 1,236 |
| Ceilcoat | 4 | 1,630 | 1,510 |
| | 6 | 2,340 | 1,620 |
| Ciba | 4 | 2,180 | 2,360 |
| | 6 | 2,800 | 1,910 |
| Fibercast | 4 | 3,380 | 2,550 |
| | 6 | 3,510 | 2,590 |
| Fiberglass Resources | 4 | 1,370 | 1,480 |
| | 6 | 889 | 841 |
| Koch | 4 | 693 | 712 |
| | 6 | 736 | 619 |

* Loads based upon pipe weight, a column of water for a 4 or 6 inch ID pipe, a shaft weighing 10 lb/ft, and a pump weight of 650 lbs.

From the creep tests, the tension test after the creep tests, and the tup test after the creep test, it appears that at least a safety factor of four should be used in determining the tensile loads. At a long-term load of less than one-fourth the tensile ultimate, the decrease in tensile and tup strength appear to be minimized and the creep rate at 125°F seems to be low. Many manufacturers suggest a safety factor as high as ten.

With knowledge about the particular well design, such as its location, what types of formations it will encounter, and the drilling and installation method, the results of these tests can provide help in selecting candidate material. If some special properties of the pipe are required many manufacturers state that by some modifications the desired qualities can possibly be obtained.

# SECTION VII

# COST ANALYSIS FOR SHALLOW WELLS

The ultimate evaluation of nonmetallic materials for water-well components involves comparing the well costs for these materials with the costs for metallic systems. The given nonmetallic material must not only meet the necessary performance requirements but it must also compare favorably with metallic materials on the basis of well costs.

The analysis of water-well costs is shown schematically in Figure 58. The cost of a well at any period in time is the sum of two cost types: (1) initial costs such as materials costs and installation charges and (2) operating costs accumulated to date. The well cost is influenced by three costs parameters: (1) well design, (2) well environment, and (3) length of well service. Identification and specification of these cost parameters is important in this comparative cost analysis since these parameters dictate the relative sizes of the various cost items. If all cost figures are known the well cost can be computed for a given well specification. The total well cost at a given date is the sum of the individual cost items under the initial cost classification plus the sum of the individual cost items under operating costs which have accumulated as of that date; i.e., well cost ($) = $\Sigma$ initial cost items $ + $\Sigma$ operating costs ($).

## A. Initial Costs

The initial costs include the materials and fabrication cost, transportation charges, and installation charges.

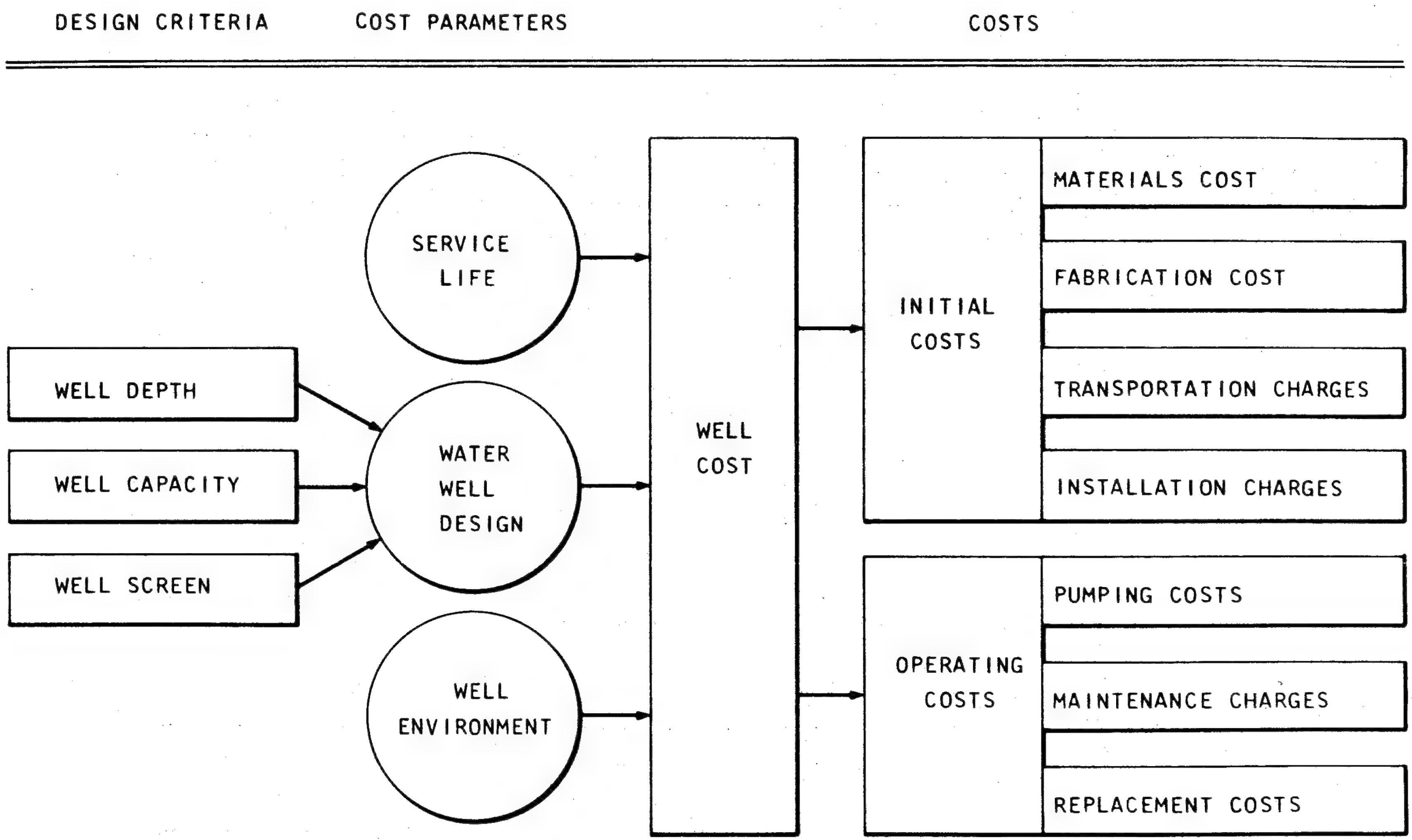



Figure 58. Schematic Of Water Well Costs

1. Material and Fabrication Costs

The relative materials costs for the various brands of FRP pipe tested and carbon and 304 stainless steel are shown in Table XVII. Even though the prices stated in this table were obtained from various manufacturers or suppliers, the costs should not be considered a binding selling price. Where possible these ratios are based on prices for 1000 ft. of pipe for May 1972. For manufacturers not submitting a price for 1000 ft. the list prices were used. The materials costs used in this study may need to be adjusted to take into account other discounts and other fluctuations in prices due to supply shortages. The pipe costs shown include couplings and glue if applicable. The coupling cost per foot is computed by dividing the length of pipe supplied by the manufacturer (varies from 10-40 ft.) into the coupling cost and is added to the pipe cost.

From Table XVII it can be seen that most of the FRP pipe tested had a lower relative cost than 304 stainless steel pipe but had a higher relative cost than common steel pipe. From other cost comparisons it can be seen that FRP pipe would not only be less in cost than stainless steel but also less than plastic and rubber coated steel[3].

As far as pipe material costs are concerned, fiberglass reinforced pipe occupies a favorable position as compared to stainless steel and some other alloys. For noncorrosive and nonencrusting situations steel pipe is materially less expensive.

Table XVIII gives the relative costs for fiberglass reinforced screen as compared to steel screen. As shown, the FRP screen compared favorably in price to carbon steel screen. The price for FRP screen is computed by taking the cost of pipe given in Table XVII and adding a slotting charge of $1-$5 per

## TABLE XVII

### RELATIVE COSTS OF FIBERGLASS REINFORCED PIPE AND STEEL PIPE*

| Pipe | | Cost Ratios 4-inch | 6-inch | 8-inch | 10-inch |
|---|---|---|---|---|---|
| A. O. Smith | with bell & spigot | 1.0 | 1.9 | 3.8 | 5.9 |
| | with standard glued coupling | 1.1 | 2.2 | 4.6 | 7.1 |
| Apex | | --- | 4.3 | 6.7 | 9.8 |
| Amercoat (Bondstrand) | | 2.6 | 4.4 | 6.6 | 8.1 |
| Brunswick | | --- | --- | 8.6 | 10.8 |
| Ceilcoat | | 3.5 - 3.6 | 5.2 - 5.4 | 6.8 - 7.2 | 8.6 - 9.1 |
| Ciba | | 1.3 | 2.4 | --- | --- |
| Fibercast | | 4.2 | 6.5 | 9.0 | --- |
| Fiberglass Resources | | 1.9 | 4.1 | 6.2 | 8.6 |
| Koch | with bell & spigot | 1.0 | 1.9 | 3.8 | --- |
| | with standard glued coupling | 1.2 | 2.4 | 4.5 | --- |
| Carbon Steel | | | | | |
| | Schedule 40 grade A53 | 0.93 | 1.6 | 2.4 | 3.5 |
| | Schedule 30 grade A53 | --- | --- | 2.1 | 2.9 |
| | Structural grade (.219 wall) | --- | --- | 1.6 | 1.9 |
| Stainless Steel | | | | | |
| | 304 welded pipe Schedule 10 | 3.9 | 5.5 | 8.1 | 10.1 |

* These ratios include couplings and glue where applicable but do not include welding costs on steel pipe if welding is used; each unit equals approximately $1.40 per foot.

## TABLE XVIII

## RELATIVE COSTS OF FIBERGLASS REINFORCED PLASTIC WELL SCREENS AND STEEL WELL SCREENS*

| Pipe | Cost Ratios 8-inch | Cost Ratios 10-inch |
|---|---|---|
| 304 Stainless steel wire wrapped rod base screen | 7.7 | 10.3 |
| Vertically slotted carbon steel | 1.2 | 1.4 |
| Fiberglass reinforced plastic | 1.0-2.7 | 1.5-3.0 |

---

* Each unit in these ratios equals approximately $6.30 per foot; the fiberglass reinforced plastic cost is based on the cost for plain pipe and a slotting charge of $1-$5 per foot.

foot. Diamond wheels are used to slot FRP screens. These wheels, though more expensive than conventional cutting wheels have an almost indefinite life and can be used in conventional pipe slotting machines. Therefore, no additional cost factors would need to be added for equipment.

Other material costs such as capital pump costs, various adapters, plugs, back pressure valves, lead seals, etc. are considered in this analysis to be approximately equal in cost for all systems. The relative cost factors for these materials for steel wells and fiberglass reinforced plastic wells would each be 1.0.

2. Transportation Charges

The second important initial cost is the transportation charges for delivering the materials. Table XIX shows the relative costs for trucking the FRP and steel pipe. Transportation charges probably would not be the same for all pipes because some suppliers may be located nearer the construction site and because different brands FRP pipe have different weights per foot. The table given takes into account the different weights per foot. The cost per pound of transporting FRP is about 2 to 3 times more expensive than steel. However, the charges per foot for FRP pipe is less than schedule 40 steel pipe and schedule 10 stainless steel pipe. The cost of FRP pipe transportation can be substantially lowered, for example, if 8-inch pipe is placed inside 10-inch pipe. The costs given take into account only straight lengths of pipe up to 40 feet in length and no inner stacking of the pipe. Another example of the transportation factor is that is some cases it could conceivably be advantageous to fly in material by plane or helicopter. The favorable weight differential for FRP pipe can readily be appreciated.

TABLE XIX

RELATIVE COSTS FOR TRANSPORTING FRP AND STEEL PIPE*

| Pipe | Cost Ratios 8-inch | Cost Ratios 10-inch |
|---|---|---|
| FRP pipe | | |
| per pound basis | 2.2-4.5 | 2.2-2.9 |
| per foot basis | 13 | 13-20 |
| Carbon steel pipe, schedule 40 | | |
| per pound basis | 1.0 | 1.0 |
| per foot basis | 29 | 41 |
| 304 stainless steel pipe, schedule 10 | | |
| per pound basis | 1.8 | 1.3 |
| per foot basis | 24 | 24 |

* These ratios are based on costs for trucking 1000 ft. of straight length pipe from Austin, Texas to San Francisco, California; each unit equals approximately 0.00254¢ per mile.

3. Installation Charges

The final initial charge to be discussed is the installation charge. This parameter is highly dependent on the productivity and quality of labor, the location of the well, the drilling method and types of formations encountered. Since it is not possible to give exact costs for these procedures a general discussion of relative FRP and steel pipe costs is given. Through personal communications (Tipton & Kalmbach, Koch, A. O. Smith, Fiberglass Resources and Fibercast) with several companies that have either had their pipe installed or have installed wells, the consensus was that FRP pipe is at least no more expensive to install and in some cases FRP pipe has resulted in lower installation charges as compared with steel pipe. To this date several thousand salt and fresh water wells using FRP parts have been installed. From information available about these well installations, it was found that at times lower installation charges result from the case of coupling the FRP pipe. When slotted ring couplings and threaded couplings are used, time is saved compared to welding steel pipe. When glued couplings are used the time required for the glue to cure is approximately the same time as is required for welding steel pipe. When using the threaded couplings some care must be used by labor to ensure against cross-threading. Generally little or no special equipment is required to install FRP pipe helping prevent high installation charges. When threaded couplings are used, molded threads are generally specified because of their better design decreasing cross-threading and preventing misalignment. If the well components are pulled and disassembled the keyed joint is advantageous because the ring is removed and the pipe disconnected. Threaded couplings are sometimes hard to remove and are sometimes

damaged. If damaged the coupling can easily be replaced. For glued couplings the pipe or coupling must be sawed through in order to remove it. Upon reinstallation new couplings would be required.

Because of FRP pipe's lightweight, less expensive equipment can be used in installing it. (Tipton and Kalmbach) When being lowered in a well, its low specific gravity (about 1.2) results in the casing string being only slightly heavier than the water it displaces, and clamping and holding of the pipe during installation process is greatly simplified.

## B. Operating Costs

### 1. Pumping Costs

The possibility of lower pumping charges for FRP pipe exists because of lower head loss for the same flow rate and inside diameter pipe. Figure 59[4] shows the head loss versus flow for various sizes of polyester or epoxy pipes and for various flow rates.

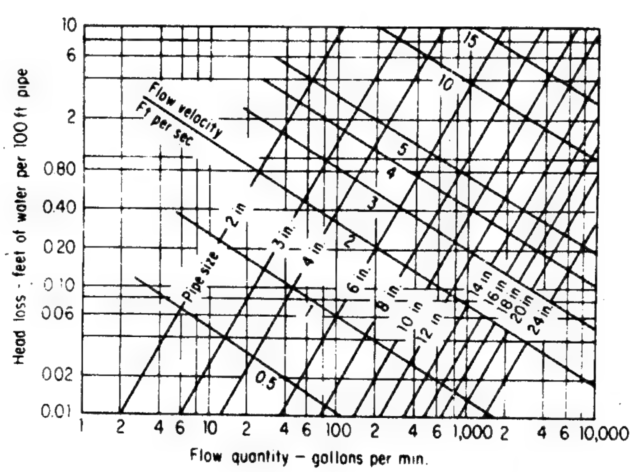



Figure 59. Head Loss Versus Flow Rate
for FRP Pipe Epoxy or Polyester @ 68°F Water

Applied to the Hagen-Williams formula, the roughness coefficient C is found to be exceptionally high for FRP pipe, being in the 150+ range. The relative friction in various pipes is listed in Figure 60[5].

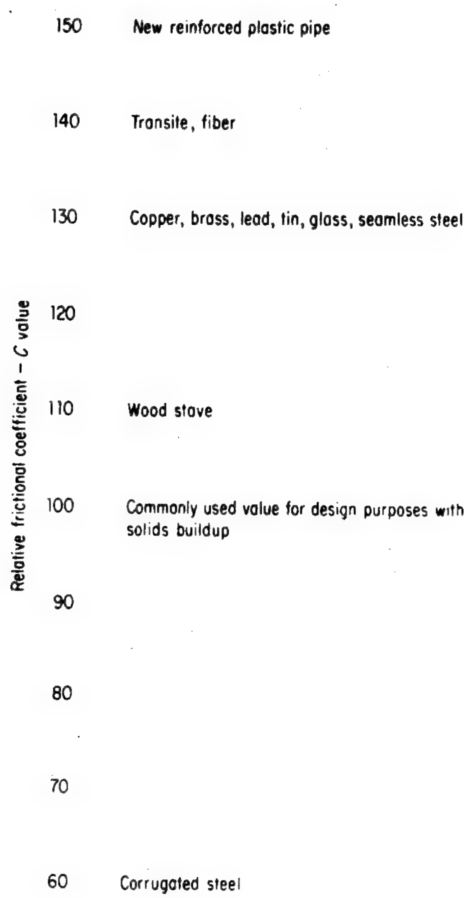



Figure 60. Relative Frictional Coefficient of Various Piping Materials

It is possible that little or no scaling will occur on FRP pipe surfaces as compared to steel pipe surfaces and that FRP pipe surfaces could be more easily cleaned. This factor would tend to reduce friction in FRP pipe.

For the engineer who uses friction factors, Figure 61[6] shows the relative roughness versus the pipe diameter for filament wound FRP pipe and commercial steel or wrought iron. Because of the decreased relative roughness the friction factor is considerably less at high Reynolds numbers.

Since the size and type of pipe and flow rate affect the head loss a specific case of 400 gal/min through 1000 ft. of 6-inch column pipe was chosen to compare steel and FRP head losses. Using $h_\ell = f \frac{L}{D} \frac{V^2}{2g}$ the difference in head loss due to friction was computed to be only about 1 foot for a total friction head loss of approximately 10 feet. This small difference is hardly enough to account for any differences in pumping charges.

2. Maintenance Charges

One of the most important cost differentials between steel and FRP type wells is the maintenance charges. The information about maintenance comes from vendors, suppliers and installers of water well systems. For example, some steel wells installed in West Pakistan experienced decreased yields after six months of operation. This decline was traced to encrustation caused by sulfate-reducing bacteria. FRP casing and screening have been used in 4000 wells there and have been performing successfully since 1965 with no problems due to the FRP designs. These wells have been operating with water of 200-3000 ppm salt. In another program 8- and 10-inch FRP casing has been used in a 1700 ft. deep well. Some companies have used FRP pipe for salt

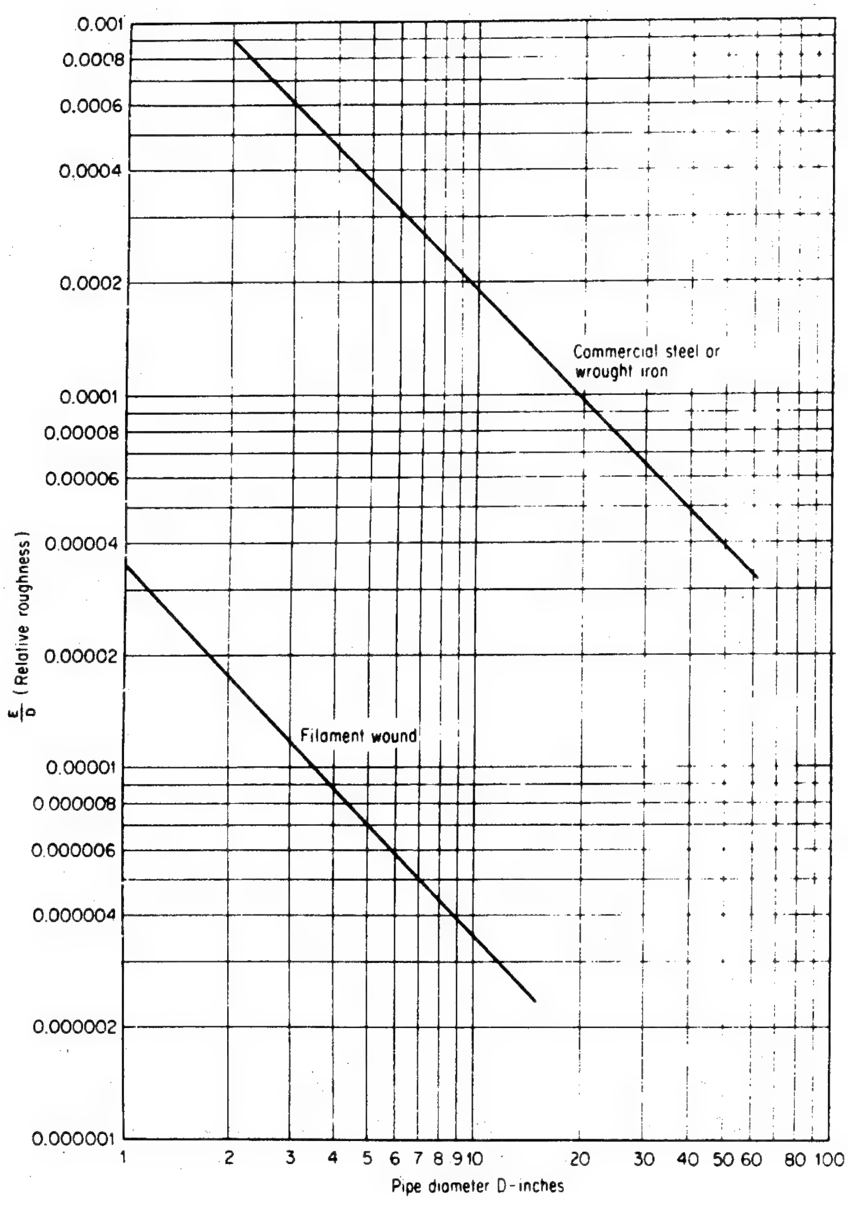



Figure 61. Relative Roughness, E/D, Versus Pipe Diameter for Filament-Wound, Commercial Steel, or Wrought-Iron Pipe

water wells for 10 years and have reported no deterioration or corrosion (Tipton and Kalmbach). In some of these cases FRP wells had little or no maintenance; whereas, the steel wells required constant attention.

In some FRP wells installed in west Texas around 1966, the only reported maintenance due to the pipe material itself was when the column pipe was pulled for pump maintenance. The threaded coupling presented some problems because of the difficulty in removing them without damage. It was stated that these couplings were replaced with no damage to the pipe itself. This maintenance was estimated to be about the same cost as for steel wells.

From these actual cases it appears that FRP wells have not presented many maintenance problems that would not have occurred with the steel pipe. In some cases the FRP screen prevented iron oxide scaling that some iron bacteria form on steel screening.

### C. Service Life and Well Environment

As has been discussed earlier many wells using FRP casing and other parts have been in service for over 10 years and are still working. At some of these places steel pipe had been tried and had shown severe decreases in capacities in as little as 6 months. In some instances where encrustation was the problem sometimes inexpensive maintenance solved the problem in the steel wells but in many cases corrosion was so severe that new materials had to be installed.

When the well environment is such that steel cannot be used other materials must be selected. From the results of Radian Corporation's tests and because of the history of successful well installations, FRP pipe appears to offer relatively long service life.

# SECTION VIII

# RECOMMENDATIONS

The purpose of this section of the report is to discuss the manner in which the data collected in this program can be utilized in the design of a particular water well system. To accomplish this optimum design and/or bid specification for a particular well, the data contained in this report can be used in the following manner.

## A. Selection of Candidate Casing Pipe

Once the type of drilling and completion techniques for a particular well is known, one can determine if it is possible to use FRP in place of steel. If FRP is to be used, an appropriate safety factor is determined. Once the safety factor is established, the materials with the requisite ultimate strength of pipe and connector can be obtained from Table XV by dividing these values by the safety factor. If the value so obtained is larger than the depth of the proposed well, the material meets this first requirement.

From the results of the tup and parallel plate tests, Tables VI and VII and Figures 36 through 39, a further selection can be made if the loads to be withstood can be estimated. This is difficult to accomplish, and experience must be used as a guide. Even so, the data can show which materials perform best under certain assumed forces. This is accomplished by subtracting the outer diameter (OD) of the column pipe from the inner diameter (ID) of the casing pipe, once the size of both has been fixed. Now, by dividing this difference by 2, a point of the maximum load and maximum deflection can be determined on Figures 36 through 39. Candidate materials can be selected from those materials whose curves lie above this point.

From Table II and the known depth of the well, the weight of the casing pipe can be calculated. If possible, it would be advantageous to have the candidate material with a tensile strength of tupped pipe greater than the weight of casing pipe times the appropriate safety factor.

B. Selection of the Column Pipe

To make a selection or bid specification for column piping for a particular installation, the data presented in this report can be used in the following manner.

Define the safety factor and the depth at which the pump or turbine is to be set. Once this has been accomplished, candidate materials can be selected by dividing the safety factor into the values listed in Table XVI. If this value is greater than the proposed depth, then the pipe is a possible candidate.

The next property that any possible candidate pipe must minimize is the rate of creep of the material. To determine this, one can calculate the long-term load to be placed on the column pipe. This long-term load consists of the pipe itself, the pump, and the water in the pipe. Typical calculated loads for various depths are shown below:

TOTAL LOAD IN POUNDS

| PIPE (INCHES) | WELL DEPTH | | |
|---|---|---|---|
| | 100 ft. | 300 ft. | 500 ft. |
| 4 | 1240-1490 | 2420-3180 | 3600-4850 |
| 6 | 2040-2290 | 4820-5600 | 7600-8850 |

where:

| | | | |
|---|---|---|---|
| 4-inch | pipe | 0.4-2.9 | lbs/ft |
| | water | 5.5 | lbs/ft |
| | pump | 650 | lbs |
| 6-inch | pipe | 1.7-4.2 | lbs/ft |
| | water | 12.2 | lbs/ft |
| | pump | 650 | lbs |

Using calculations such as this, the load can be approximated and the creep rate of a pipe at this load can be found in Table IX. The pipe that minimizes this creep rate would be most advantageous.

From Tables XI and XII for the tup after creep test and the tension after creep test, the candidate materials can be further evaluated. The materials of most interest, of course, are those that display the least decrease in strength caused by the long-term tensile stress.

### C. Selection of Well Screen

As seen in Table VIII, the steel screen is the stronger of the materials tested. If the well is to be in an area where encrustation is a known problem, and the formation pressures not too great, the FRP screen could be easily used. It is also interesting to note that the steel screen is not a great deal stronger than the strongest FRP; therefore, the FRP could be used if the well completion technique used is not of a drastic nature.

Utilizing the data obtained in this program in the above manner, an optimum water well system can be designed and

specifications written for the procurement of the installation. Also, there will most probably be more than one material that will meet all qualifications necessary and thus another fallout will be a prospective bidders' list to ensure the most competitive price possible for the Air Force.

# APPENDIX I

# SURVEY OF WATER WELL INSTALLATION AND MAINTENANCE TECHNIQUES

## SECTION I

## INTRODUCTION AND SUMMARY

The purpose of this appendix is to review the techniques used in the drilling of water wells. Primary consideration is given to the mechanical stresses imposed on the pipe and the well screen by the different drilling techniques and the methods utilized in setting casing and well screen. In addition, chemical treatments involved in the disinfection of the well after completion are reviewed. The methods utilized to reestablish the initial yield of the well in the event of plugging or corrosion of the screen (if metallic) are also considered.

A variety of methods is used to drill water wells. Some of these are not applicable to the use of nonmetallic materials because of the large mechanical stresses involved. Of the methods presently utilized three seem suitable for applications in which the casing and screen materials are of lower mechanical strength than steel. These methods are (a) the earth auger method, (b) the hydraulic rotary drilling method, and (c) the reverse rotary drilling method. The reverse rotary drilling method appears to have the greatest promise in this application and will be carefully evaluated later in this program.

Water wells must withstand a chemical environment during disinfection procedures and in the procedures for cleaning plugged screens. Chlorine, sodium hypochlorite and calcium hypochlorite are commonly used in the disinfection of water wells. Screens are often plugged by insoluble carbonates. When this occurs hydrochloric acid or sulfamic acid is added

to the well. The well materials are usually in contact with significant concentrations of these compounds for only a short period of time. In contrast to this short period of time, the casing of the well will be exposed to water and soil bacteria for the lifetime of the well.

In severe cases of plugging, where the acid treatment is unsuccessful, the well is blasted with dynamite or primer cord to remove clogging. This shock treatment seems to be the most severe form of mechanical attack that the well screen has to withstand. However, it can be anticipated that noncorrosive materials will show a lower tendency to scale formation[7] since the pH increase at the anodic sides of iron during corrosion favors calcium carbonate deposition even from equilibrium waters.

This review is based upon some of the most authoritative sources of water well technology[8]. The findings of this review are that techniques are presently in use which should allow the use of nonmetallic materials in Air Force potable water applications.

Subsequent sections of this review are devoted to the four distinct operations usually necessary for completing and maintaining a water well as follows:

. Drilling and Casing Installation

. Installation of Well Screen

. Disinfection and Development

. Maintenance of Well Yield

## SECTION II

## DRILLING AND CASING INSTALLATION

There are eight common drilling methods as listed below:

- Cable Tool Percussion Method
- California Stovepipe Method
- Hydraulic Rotary Drilling
- Reverse Circulation Drilling Method
- Jet Drilling Method
- Hydraulic Percussion Method
- Earth Auger Method
- Air Rotary Drilling Method

The most economical method to use in a particular case depends upon the purpose of the well, the geological formation encountered, the well diameter, the depth, and the ease of construction.

### A. Cable Tool Percussion Method

The cable tool percussion method is mainly used in small diameter wells. A heavy string of drilling tools (Figure 62) consisting of drill bit, drill stem, drilling jars and rope socket is lifted and dropped regularly in the borehole. The

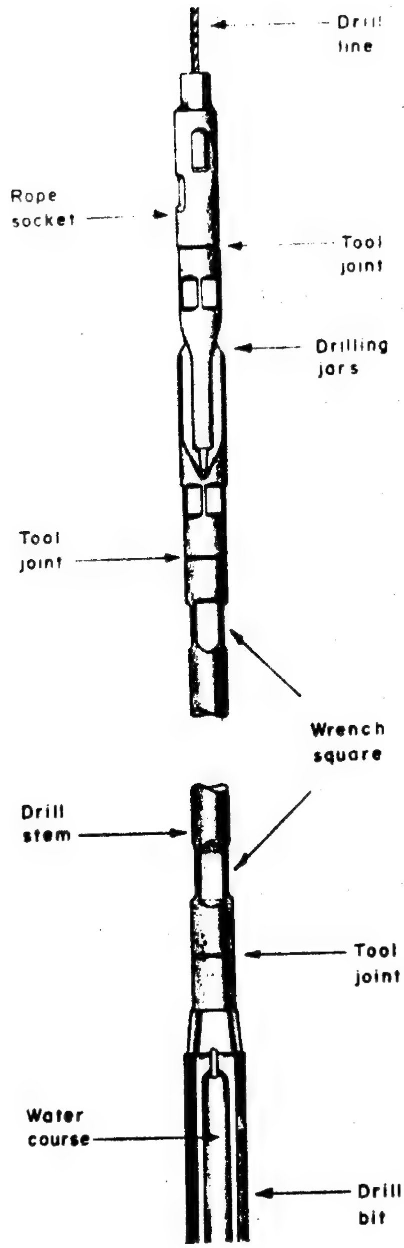



Figure 62. Four Components Of The String Of Drill Tools For Cable-Tool Percussion Drilling.[8]

borehole is partly filled with water. The slurry and sludge formed during the drilling operation is removed periodically by means of a sand pump or a bailer.

In hard or consolidated formations the borehole can be driven without setting the casing until the water bearing aquifer is reached. In these cases the drilling operation and the installation of the casing are two distinct steps.

In a soft or unconsolidated formation however, the casing must follow the drill bit very closely in order to prevent caving and to keep the borehole open. The usual procedure is to drive the casing from one to several feet in front of the drill bit, thus forming a plug inside the casing. This plug is mixed with water as the drilling operation continues. The slurry is then removed, the casing driven again and the operation repeated. The friction at the outside of the casing becomes greater the deeper the borehole is driven. When the friction on the outside of the pipe becomes so great that further driving may damage it, a string of pipe smaller in size is used to continue. On occasion this operation must be repeated several times. Therefore, the size of the drill hole at the start is larger than is ultimately required.

It is obvious that in drilling operations in soft or unconsolidated formations only steel casings can withstand the mechanical forces applied.

### B. California Stovepipe Method

The California stovepipe method differs from the cable tool percussion method in three respects.

- A heavy bailer (mud scow) is used for simultaneous drilling and bailing.

- Laminated steel casing in short length is used.

- The driving of the pipe is done by hydraulic jacks rather than driving the casing by the impact of the tools.

Before starting the drilling operation a pit is dug and the hydraulic jacks, the anchors for the jacks, and a starting pipe approximately 10 feet in length are installed. The commonly used stovepipe casing is about 4 feet long. The pieces are slipped together with the outside casing overlapping the inside part by half of its length. The wall thickness of the cylinders used is too small to provide the mechanical strength for withdrawing the casing when the water bearing aquifer is reached as is often done to set a well screen. Most commonly, a casing perforator is used to puncture the wall casing in the water bearing strata. The irregularity of the resulting holes sometimes results in sand pumping wells.

The method can be modified to use regular line pipe casing thus allowing the setting of a regular screen. The mechanical impact on the casing is not so great as it is using the cable tool percussion method because the pipe is not driven in front of the bit. The applied mechanical forces have still to overcome the friction between the outside of the well casing and the borehole.

## C. Hydraulic Rotary Drilling Method[10]

Hydraulic rotary drilling or direct rotary drilling with mud is a most common and widely practiced procedure. It was first developed by the mining industry and was later adopted by the petroleum industry. The distinguishing feature of this technique is that the drilling mud is forced by means of a pump down through the inside of the drill pipe and out through openings in the bit. The mud then flows upwards through the borehole into a settling pit. The consistency of the drilling mud is most important in this technique. Its primary functions are:

- A substitute for casing - In most all cases the mud film formed at the wall of the borehole provides a seal until drilling is finished and the casing is set.

- To remove cuttings from the hole - To provide this function the viscosity, the specific weight and the streaming velocity must be balanced with respect to each other. Not only the removal of the cuttings from the borehole must be considered but the cuttings must be able to settle in the surface settling pond.

- To prevent caving - The pressure against the wall can be varied for a given hydrostatic pressure by means of the specific weight of the drilling mud. At the point where the hydrostatic pressure of the drilling fluid column is greater than the water or gas pressure in the formation, gas or water in the formation will be confined.

- For lubrication and cooling - The lubrication properties of the drilling mud minimize wear of the drill bit and lower power requirements. The circulating fluid provides effective cooling of the drill bit.

- To prevent loss circulation - Drilling mud accomplishes this task by sealing the capillaries in the formation. The critical parameter for achieving capillary sealing is the colloidal content of the mud.

Hydraulic rotary drilling can be applied to any formation encountered. The industry offers soft formation rock bits, medium to hard formation rock bits, hard formation rock bits, and very hard formation rock bits.

New tool developments for application to the conventional drilling systems are down-the-hole tools such as the turbo drill and vibrating drills.

The drilling operation and the installation of the casing are two distinct steps in this drilling method. Thus, no mechanical impact is applied to the well casing during the drilling operation itself.

There are several disadvantages to using hydraulic rotary drilling.

- To raise large particles to the surface, heavy mud (high specific weight) and high ascending velocities between the drill pipe and well wall are necessary. Therefore, it is not well adapted for drilling formations having heavy gravel or stones.

- With increasing diameter of the hole the velocity drops to a point where large particles will not rise.

- The heavy drilling mud necessary to raise large particles seals the water bearing strata to an extent which makes the development of the well sometimes difficult.

## D. Reverse Circulation Drilling Method[11]

Most of these disadvantages listed above are avoided in using the reverse circulation drilling method. In this method the direction of the fluid stream is reversed from that utilized in the hydraulic rotary method (Figure 63). The water stream with its burden of material loosened by the drill bit is drawn up the drill pipe by a centrifugal pump, discharged into a sump which results in only slightly muddy water being returned by gravity into the hole. The water is circulated at a rate of about 1000 gpm. The streaming velocity in a 6-inch drill stem is therefore about 680 ft/min. The water passing downward in the hole is moving with about 1/20th of this rate, thus avoiding washing or caving. The reverse circulation drilling offers the cheapest way to drill large boreholes. It is utilized for wells preferably in the diameter range of 10-60 inches. Depths down to 800 feet have been drilled successfully. In loose unconsolidated formations, penetration rates in the range of 2 feet per minute and more than 40 feet per hour can be reached. The disadvantages of the method are:

- Drilling in formations containing cobbles or boulders larger than the drill pipe. As soon as a few of these have assembled at the bottom, the drilling operation

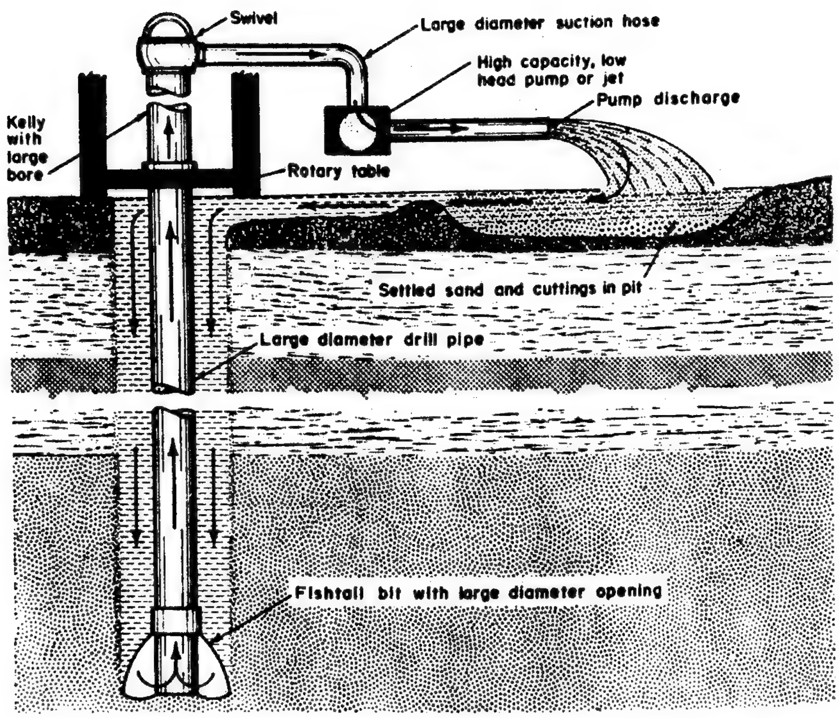



Figure 63. Basic Principles Of Reverse-Circulation, Rotary Drilling Are Shown By This Schematic Diagram. Cuttings Are Listed By Upflow Inside Drill Pipe.[8]

must be interrupted and the cobbles removed by a so-called orange peel bucket.

. Water losses in penetrating loose gravel formations are quite high and can reach 500 gallons per minute. Therefore, a large supply of makeup water must be provided. The necessity for makeup water is a function of the permeability of the formation and can be quite low (~ 20 gpm).

The borehole stays open until the drilling operation is completed. Then a casing and well screen are set and loose gravel placed around the well screen. The screen and well casing are not affected by the drilling operation itself.

## E. Jet Drilling Method

Jet drilling is used principally to drill small diameter holes with a diameter of 3 to 4 inches to a depth of about 200 feet. A chisel shaped bit is attached to the string pipe. Water is pumped through the drill pipe and issues at the bit. The drilling string is lifted and dropped as in the cable tool percussion method. The main difference is that the borehole is filled completely with water. To increase the cutting effect the whole pipe string is rotated by hand.

An open hole can be drilled to limited depth. However, whenever caving occurs, the casing must be lowered rather close to the chisel. In this case the pipe is driven using a drive block attached to the upper end of the casing.

In very soft formations small diameter pipe and well points with open bottoms can be sunk by the washing action of a water jet alone. To prevent caving the casing must follow the bit very closely.

F. Hydraulic Percussion Method

This method uses equipment similar to the jet drilling technique. The main difference is that a back check valve is provided between the bit and the lower end of the drill pipe. Also, the water circulation is reversed. Water is added at the surface in the annular space between the drill rods and well casing to keep the hole full of water.

The drill bit and rod are lifted and dropped with quick short strokes. During the dropping phase water with cuttings enters the port of the bit. This fluid is trapped when the ball check valve closes during the lifting phase. Continuous reciprocating motion produces a pumping action to lift the fluid to the top of the string of drill pipe.

G. Rotary Bucket Drilling Method

This method is used to drill large diameter but more shallow wells with gravel packing. The hole is drilled using a large diameter auger bucket. The material being excavated is collected in a cylindrical bucket which has auger type cutting blades on the bottom. The bucket is attached to the lower end of a kelly bar which is rotated by a rotary table. The bucket when filled must be lifted and the drill rods disconnected. After the bucket is emptied, it is lowered again and the procedure is repeated.

The primary application of the rotary bucket drilling is in clay formations. In penetrating sand formations blind steel casing is used to prevent caving. Boulders create problems; they must be removed with orange peel buckets.

The casing is sunk after the borehole is completed. Gravel packing and removal of the blind casing are the next steps.

### H. Air Rotary Drilling Method[13]

A relatively new development is air rotary drilling. Compressed air at a pressure of 100 to 200 psi is forced down the drill pipe. The bit is provided with ports. The velocity of the air outside the drill rod of about 3000 feet per minute removes the cuttings.

The largest size bits commonly used have a diameter of 6 to 8 inches.

Air rotary drilling has the following advantages:

- Drilling mud is not required
- Fast penetration
- Fast return of cuttings
- No contamination of cuttings
- Method does not mud off a producing formation

Difficulties are encountered in penetrating water bearing formations or formations which tend to cave. In these cases conventional methods must be applied. After casing of the unconsolidated or water bearing strata, the drilling operation can be continued using air rotary drilling.

## SECTION III

## INSTALLATION OF WELL SCREEN

The methods used in setting well screens depend to some extent on the drilling techniques applied. In cases where the drilling operation and the installation of the casing are two distinct steps (hydraulic rotary drilling, reverse circulation drilling, earth auger method) the screen can be attached permanently to the casing. In this case the installation of the casing and the installation of the well screen is one operation. The use of telescope size well screens is applicable for all drilling techniques. Telescope size well screens can be put in place by the pull back method, the bail down method, the wash down method or when well points are used by mechanical driving only.

### A. Installation of Screens Permanently Attached to the Casing

Well screens permanently attached to the casing have the inherent disadvantage that the screen cannot be replaced in case of damage. In addition it can only be used in open holes. In this case screen and casing are lowered together. The area around the screen is filled with gravel in artificially gravel-packed wells. The well is then grouted to provide sanitary protection.

In naturally developed wells a washing procedure is applied to set the screen in place. In this operation cuttings or heavy mud which may have assembled on the bottom of the hole is removed. Figure 64 shows a schematic of this technique. The temporary wash pipe and the ring seal are removed when the screen sits in place.

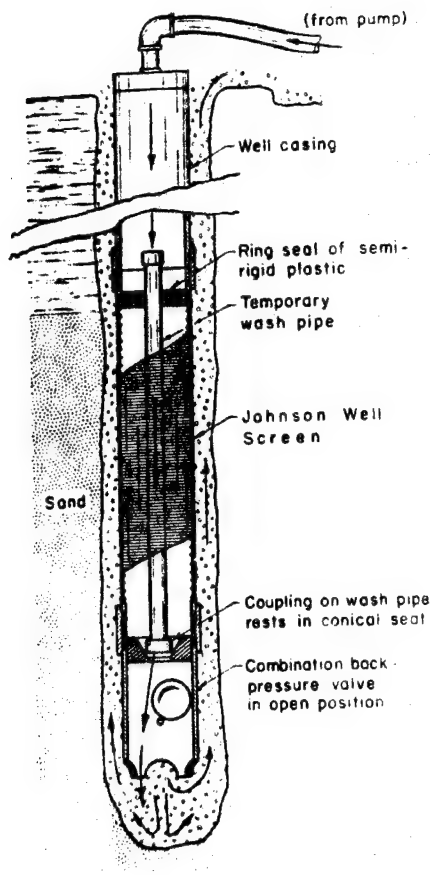



Figure 64. Small-Diameter Screens Can Be Washed Into Place By Jetting Through Temporary Wash Pipe and Wash-Down Bottom With Floating-Ball Valve[8]

B. Installation of Telescope Size Well Screens

Telescope size well screens can be used for all drilling methods. Several methods are used for their installation.

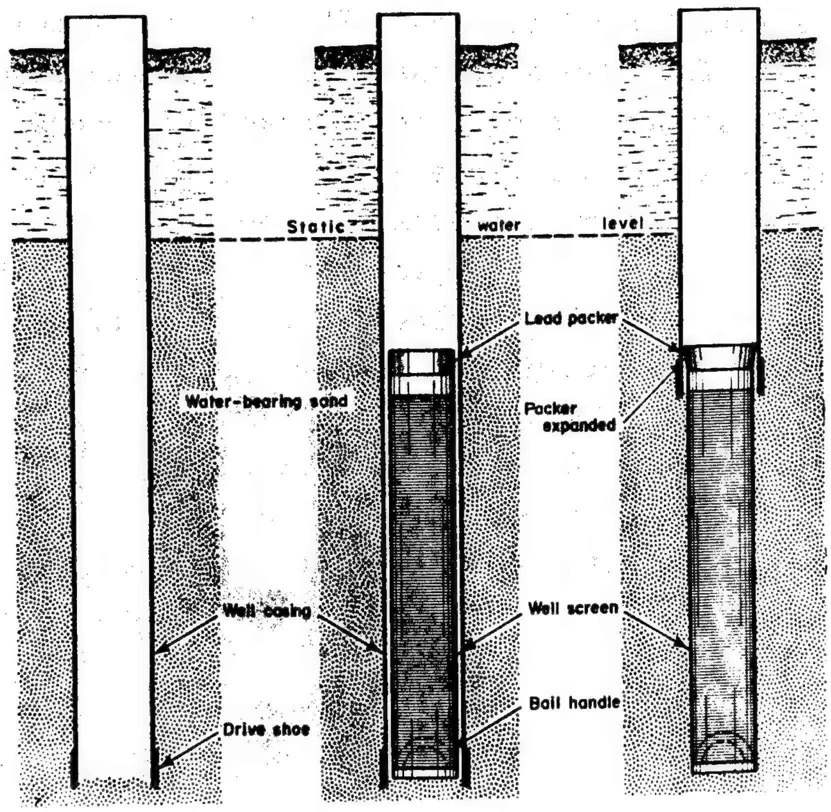
1. Pull Back Method

The basic operations in setting a well screen by the pull back method are illustrated in Figure 65. First the well casing is lowered to the final depth of the well. The area exposed to the water bearing strata can be gravel packed if necessary. Then the telescope sized well screen is put in place and the entire outside casing is pulled back to expose the screen to the water bearing formation. A lead packer is attached to the top of the screen place, thus preventing the entrance of fine sand into the inside of the screen and casing.

Conditions sometimes make it prohibitive to pull the whole string of casing back. The friction between casing and outside formation can get so great that the required pulling force can cause damage to the pipe. In this case one of the following methods must be used.

2. Bail Down Method

The well screen is filled with a bail down shoe as shown in Figure 66. The bail shoe is attached to a bailing pipe and the whole string lowered inside the casing in telescope fashion. Through the inside of the bailing tube, drilling tools or the bailer are sunk to remove the sand under the screen. The screen lowers, driven by its weight and that of the attached bailing tube. When the screen is in position the bailing tube is disconnected and the lead packer expanded.




Casing Is Sunk To Full Depth Of The Well, Well Screen Is Lowered Inside The Casing, And Casing Is Pulled Back To Expose The Screen In The Water-Bearing Sand.[8]

Figure 65. Basic Operations In Setting A Well Screen By The Pull-Back Method.

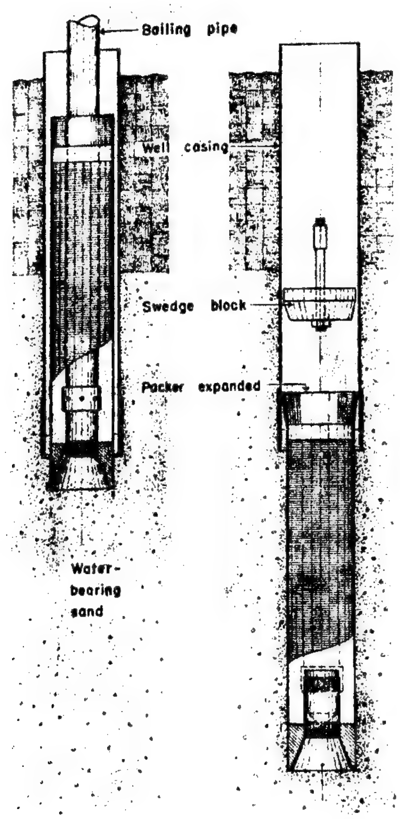



Figure 66. Assembly Of Well Screen And Bail-Down Fittings At Start Of Operation (Left), And Final Step In Completing The Screen Installation By The Bail-Down Method (Right).[8]

In heavy sand or to check if boulders are present, a small pilot hole is drilled before the bail down operation starts (see Figure 67).

3. Wash Down Method

The essential details of this method are shown in Figure 68. The screen is attached to a string of wash line and lowered in place. The self-closing valve is opened when a high enough water pressure is built up in the wash line. The jetting action of the water loosens the sand and the screen sinks driven by its own weight and that of the wash line.

When the screen is in place the wash line is removed and the lead packed expanded. A disadvantage of the wash down method is the fact that larger sand particles settle inside the screen and have to be removed.

A simpler design is shown in Figure 69. Because the wash down bottom is not self sealing in this case, the hole on the bottom of the screen must be sealed. A common technique is the use of lead shot or lead wool.

4. Setting of Well Points

In small diameter wells the screen can be driven into the water bearing stratum by mechanical forces only. There are two methods commonly in use. The first (Figure 70) drives the well point with a driving weight. When driving relatively long well points the use of a driving bar is preferred. This method directs the mechanical forces to the bottom of screen thus minimizing the danger of collapsing (Figure 71).

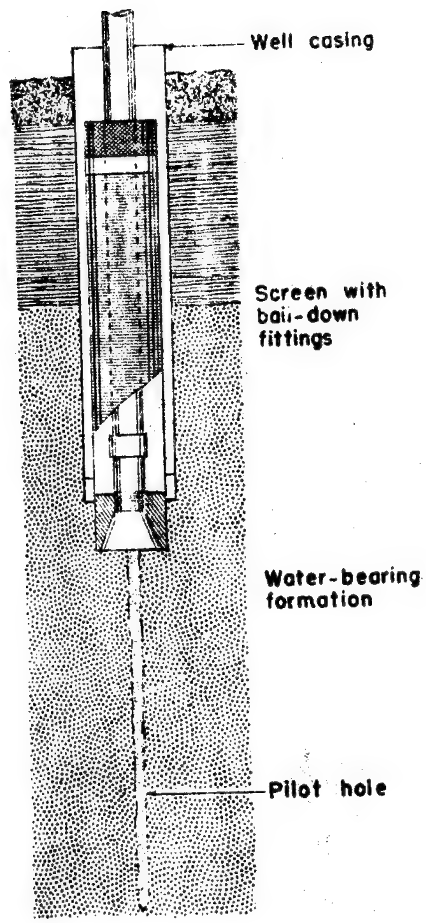
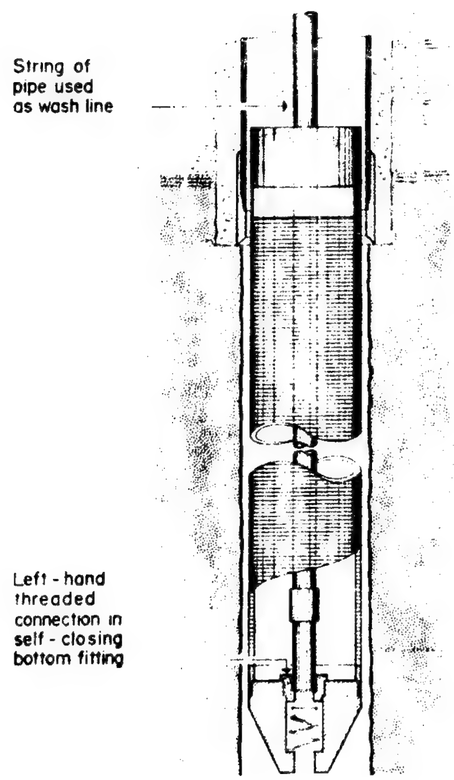



Figure 67. Pilot Hole, Drilled Into Aquifer Before Starting To Install A Well Screen By the Bail-Down Method, Assists The Operation.[8]




Space Around The
Lead Packer Allows Return Flow Outside The Well Screen.[8]

Figure 68. Wash-Down Bottom With Spring-Loaded Valve Permits Washing Screen Into Place.

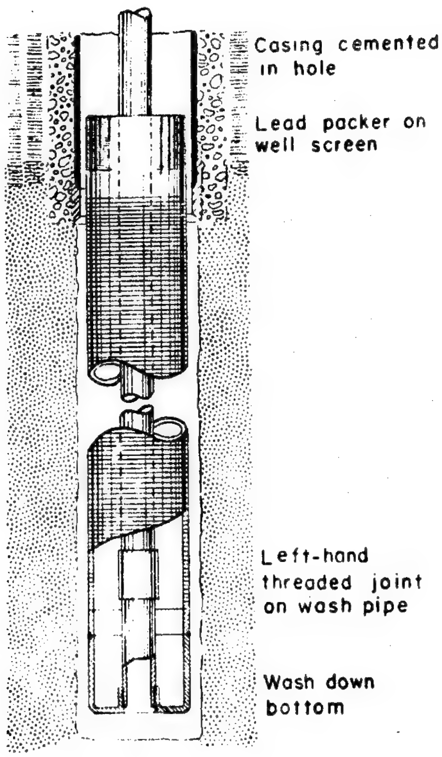



Figure 69. Simple Design Of Wash-Down Bottom Without Valve.[8]

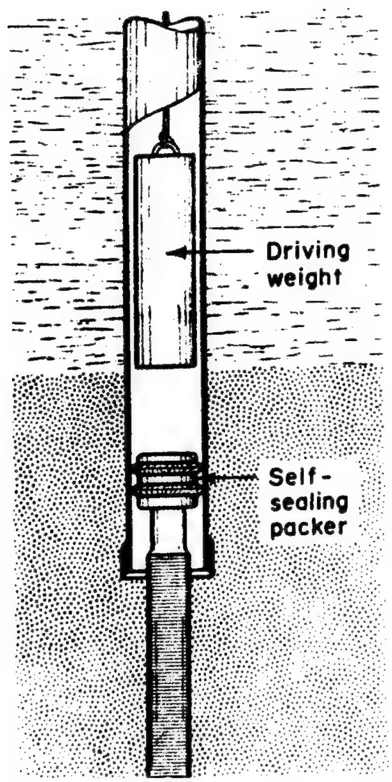



Figure 70. Drive Well Point, With Self-Sealing Packer Attached, Can Be Driven Into Water-Bearing Sand Below End Of Casing.[8]

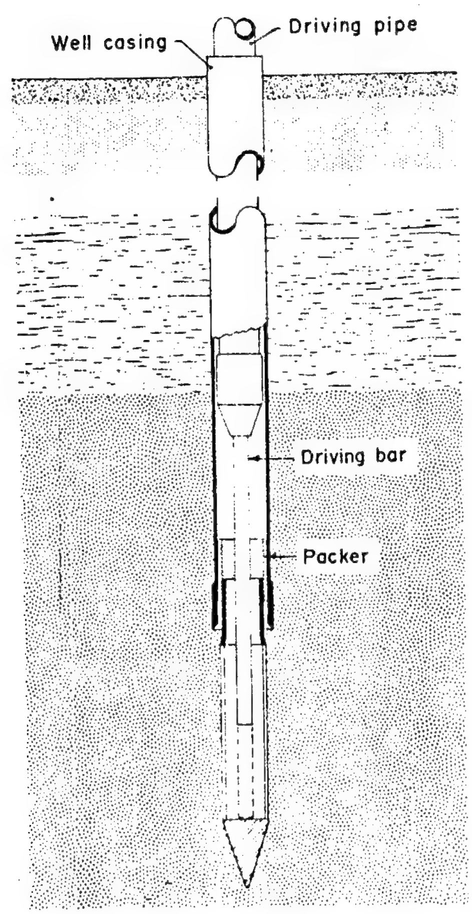



Figure 71. Driving Bar Which Delivers Force Directly On Solid Bottom Of Drive Well Point Is Useful For Driving Well Points 5 Ft. Or Longer.[8]

## SECTION IV

## DISINFECTION AND DEVELOPMENT

After the casing and well screen are set, the upper areas of the well are grouted or cemented for sanitary protection and the well is developed. In the development phase finer sand particles around the well screen are removed thus providing the maximum capacity. The procedures applied in this phase are not of interest here since no mechanical or chemical procedures are used which might damage the pipe in any way.

A necessary final step is the disinfection of the well and piping. The chemicals used are chlorine which forms hydrochloric acid ($HCl$) and hypochlorious acid ($HClO$) when dissolved in water, sodium hypochlorite solutions ($NaClO$) and calcium hypochlorite solutions ($Ca(ClO)_2$). The disinfection is based on the oxidizing character of these solutions. The concentrations normally used are 50 to 200 ppm.

The disinfectant solutions are left in the system for at least 4 hours. The casing material chosen for well construction must be resistant to these chemicals.

## SECTION V

## MAINTENANCE OF WELL YIELD

The original yield of a well can decrease during operation because of incrustation and corrosion of the screen and corrosion of the casing.

Incrustation is caused by the deposition of calcium and magnesium carbonate and of calcium sulfate in waters of high sulfate content.

Corrosion of iron pipe and screens occurs in aggressive waters with high $CO_2$ and $O_2$ content. Another corrosion danger arises from sulfate reducing bacteria which act as depolarizers.

Although both mechanisms are basically different, they have a harmful affect when occurring together. In the corrosion of iron an increase of the pH occurs at the anodic sites which causes the precipitation of $CaCO_3$ even from equilibrium waters.

The remedies used in clogged wells are acid treatment to dissolve the carbonate layers and the iron oxides formed by iron corrosion. The acids most commonly used are hydrochloric and sulfamic acid containing corrosion inhibitors. Both acids form highly soluble calcium compounds. Sulfate reducing bacteria are killed with chlorine. Sometimes the layers of scale and corrosion cannot be removed by these treatments. In this case the openings in the screen and the water bearing stratum are freed from incrustation by means of primer cord or dynamite.

Corrosion of iron screens was observed to occur preferentially at the slots, thus enlarging the inlet openings. This finally results in sand pumping wells. In these cases the well screen must be replaced and preferably the materials of

construction changed. The danger encountered here however is the establishment of a galvanic cell between screen and the iron casing.

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13. ABSTRACT

(Distribution Limitation Statement A)

The use of fiberglass reinforced plastic pipe for water well applications was investigated. To carry out this investigation, a test program and test procedures were developed due to the unavailability of uniform test methods for plastic pipe for this application. The apparatus necessary for the test program, including long and short term tension tests as well as biaxial, point and uniform load compression tests and combinations of these tests, was constructed and the tests performed on commercially available plastic pipe from several manufacturers. The results of these tests allow comparisons of the physical properties of the nine manufacturers' pipe tested. These data are compiled in such a manner that they can be utilized to design an optimum well system for any particular installation.

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